Adaptive Software defined Terabit TRansceiver for flexible Optical Networks

Project number: 318714
Duration: 10/2012 - 3/2016
Total Cost: 4.6M €
EC Contribution: 3.2M €
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Download the final publishable summary of the ASTRON project

Download the Overview Presentation of the Overall Progress of the ASTRON project

Project Summary

ASTRON project aimed at the design and development of an integrated optical transceiver (Tx/Rx) that enables the wide and cost-efficient deployment of flexible core and access networks.

The main features of the Tx/Rx are the following:

- Reconfigurable bandwidth allocation using either Optical OFDM or Nyquist WDM technology
- Programmable modulation formats
- Programmable data rate
- Programmable FEC (offering tunability of the ratio of the actual payload to the FEC)
- Energy-efficiency by incorporating state-of-art digital, analog, mixed-signal and optical components into an integrated platform
- Design for Manufacturability using components that can be easily produced at low cost embedded into a compatible package

The implementation of such a system provide a low-power and low-cost alternative to the use of expensive and power hungry transceivers made from discrete components. The transmitter and receiver modules are designed to be packaged into a small form factor module in order to be compatible with the current network devices. During the ASTRON project the design and the development of compact and scalable photonic integrated components as well as all the necessary electronic circuits and state of the art algorithms to drive and control the optical devices were realized. These devices are capable of generating and receiving advanced-modulation-formats (QPSK, 16 QAM) encoded optical signals for high capacity (beyond 1Tb/s) networks. The unique features of the ASTRON architecture allow the transmitter to dynamically support different transmission technologies (optical OFDM or Nyquist WDM) and due to the advanced software-defined signal processing, the proposed system supports different data rates providing flexibility and efficiency[1].

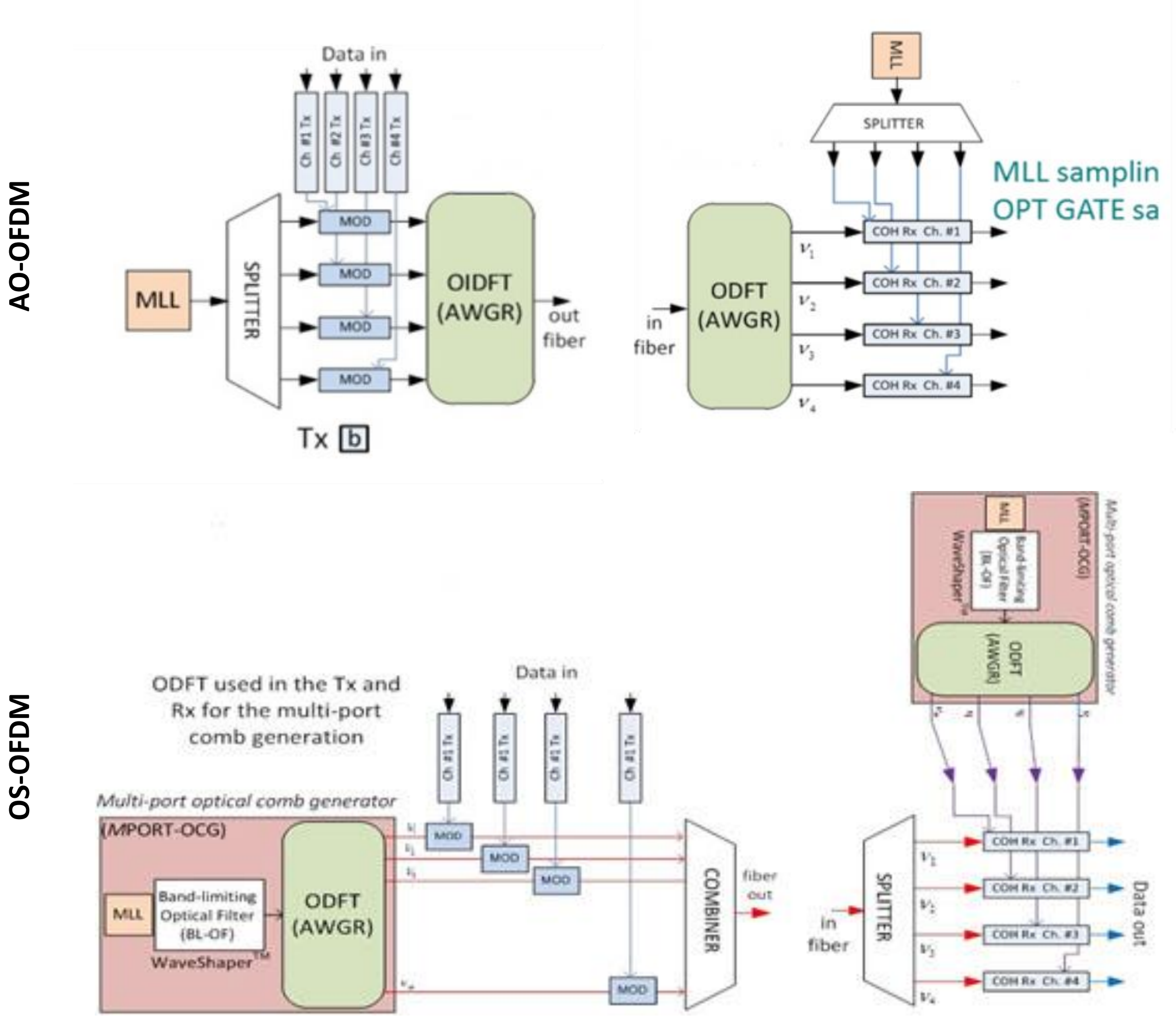
WP2: System Architecture and Requirements

In the framework of the ASTRON project, two complementary configurations of Terabit OFDM transceivers were proposed, allowing energy-efficient and bit-rate flexible operation with rates from 10 Gbps to beyond 1 Tbps.
The ASTRON concept combines monolithic and hybrid integration to develop, for the first time, complex super-channel OFDM/Nyquist-WDM transmitters and receivers relying on integrated arrayed waveguide gratings (AWG) for performing the inverse discrete Fourier transform/discrete Fourier transform (IDFT/DFT) in the optical domain. The two complementary configurations (**OS-OFDM** and **AO-OFDM**) are shown in the figure below, the main difference being that the position of the splitter/combiner and the AWG are reciprocally inverted. A variant of the AO-OFDM

[1] P. Zakynthinos, G. Cincotti, M. Nazarathy, R. Kaiser, P. Bayvel, R. I. Killey, M. Angelou, S. B. Ezra, M. Irion, A. Tolmachev, B. Gomez Saavedra, J. Hoxha, V. Grundlehner, N. Psaila, G. Vollrath, R. Magri, G. Papastergiou and I. Tomkos, "*Advanced Hybrid Integrated Transceivers to Realize Flexible Terabit Networking,*" IEEE Photonics Society News, vol. 28, no. 1, pp. 12-19, 2014.

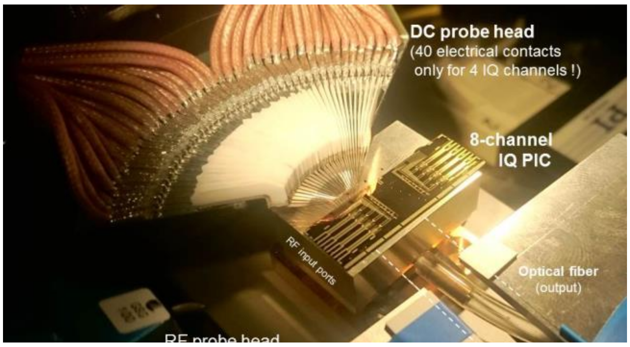
scheme using single polarization and direct detection (DD) without chromatic dispersion compensation was also investigated for access/metro networks in compliance with existing (and coming soon) passive optical network (PON) standards.

Those transceiver designs have been compared with each other and with other competing transceiver designs in terms of their cost and power consumption. Due to photonic integration and low complexity DSP the ASTROON designs appear to be cost effective and energy efficient solutions for 1Tb transceivers.



AO-OFDM (a) and OS-OFDM (b) transceiver architectures. MLL: Mode-locked laser.

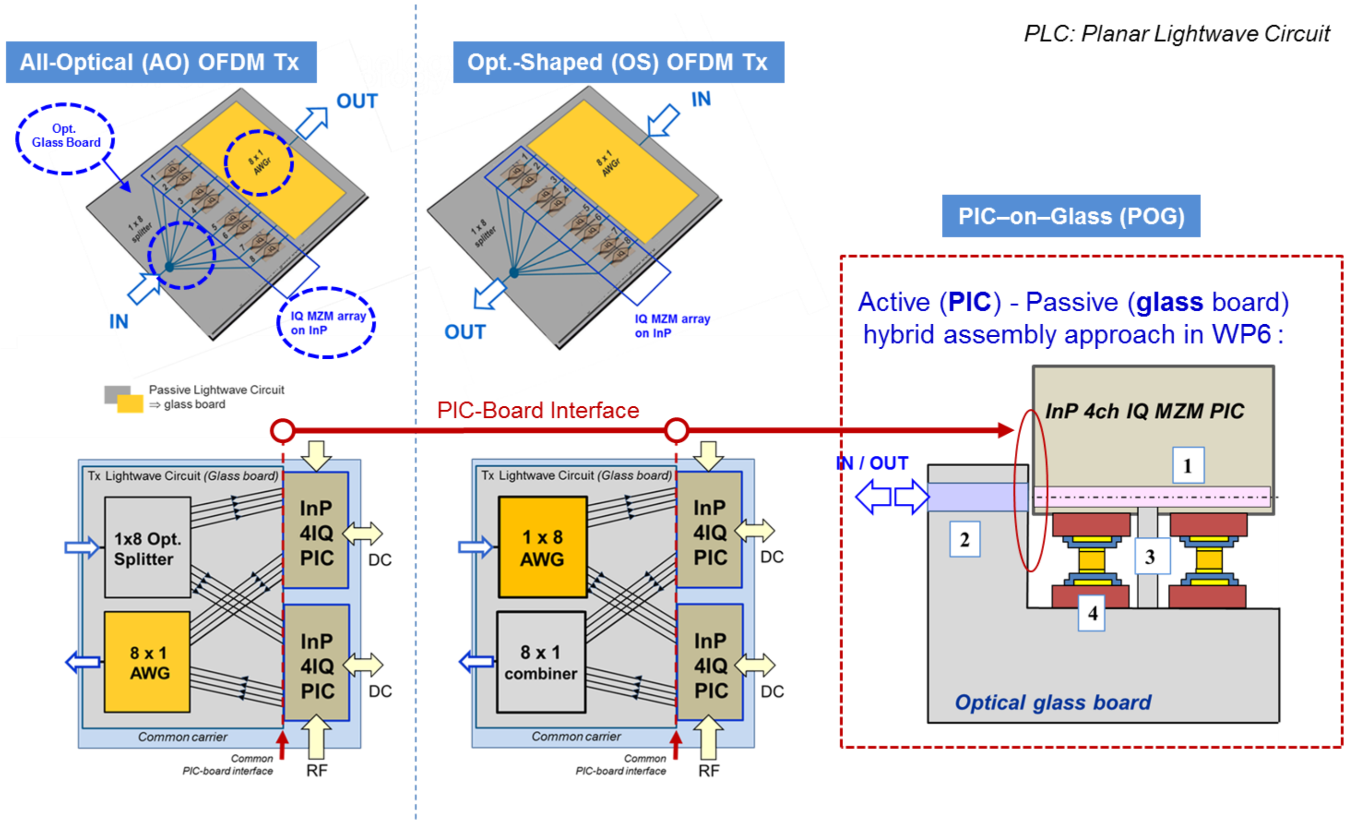
WP3: Integrated Transmitter Module



Photograph of two 4-channel (Quad) IQ InP PICs connected to a specifically designed and fabricated electrical 44-lines DC probe head while measuring the electrical performance characteristics on the test station. The electrical RF probe head is also shown as well as the optical input/output fibers attached to a single PIC interface.

The design, fabrication and characterization of **monolithic 4-channel (Quad) and 8-channel Mach-Zehnder (MZ) In-phase Quadrature (IQ) modulator PICs (IQ PICs) on InP** was finished. These IQ PICs are used **as active building blocks** for hybrid assembly with the passive optical planar glass motherboard in work package WP6. The board integrates all passive optical transmitter (Tx) functions of the hybrid 8-channel OFDM/N-WDM ASTRON transmitter planar lightwave circuit (PLC)[2].

In the **PIC-on Glass (POG)** hybrid integration approach, the active InP IQ Mach-Zehnder modulator array chips are directly assembled onto a glass board as common integration platform by using flip-chip eutectic bonding and precise pick-and-place techniques. The optical glass board integrates all required passive optical Tx functions (splitter, AWG, retiming) as well as all required electrical DC and RF tracks and connections.

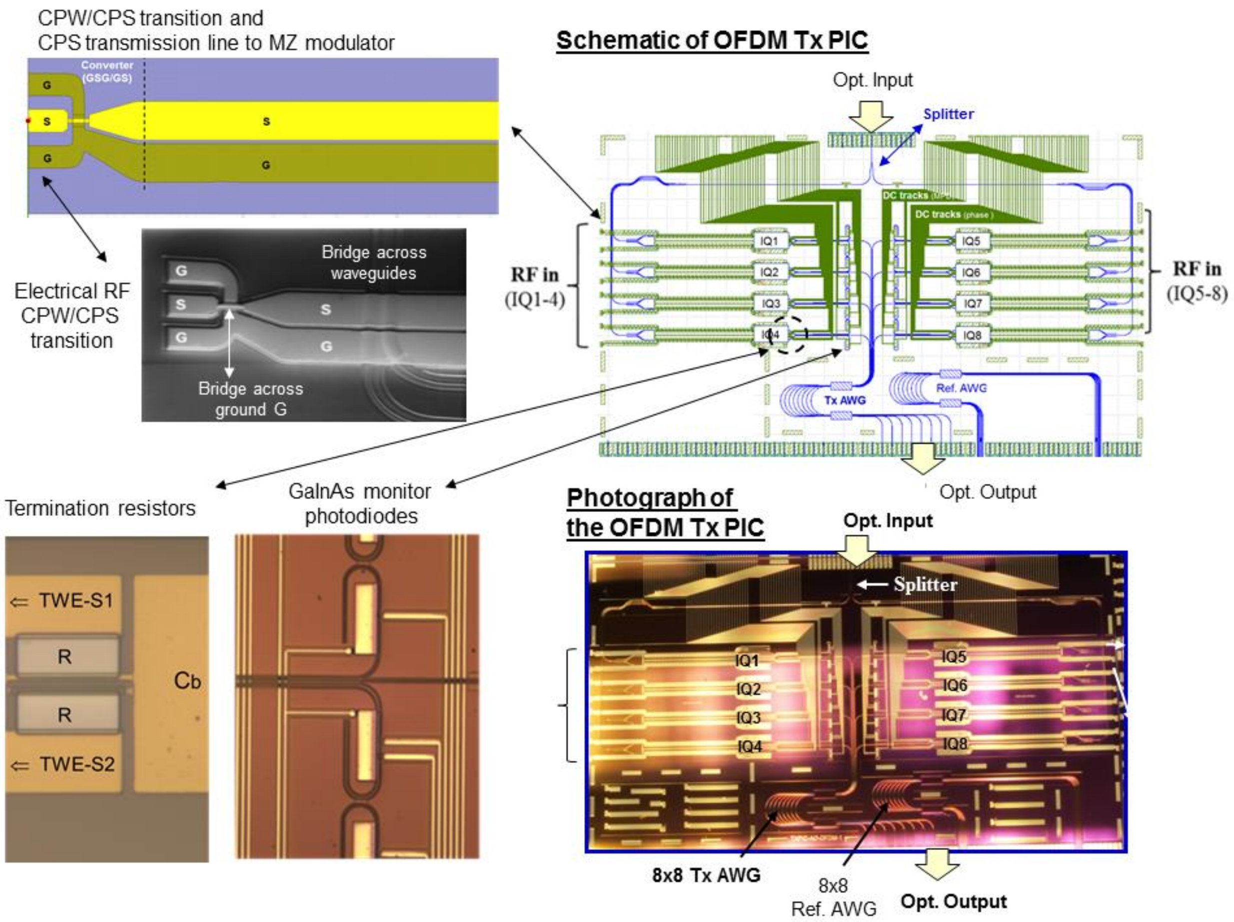


Schematic of an 8-channel all-optical OFDM Tx (AO-OFDM, top left) and an optically shaped OFDM Tx (OS-OFDM, top right) and the relevant schematics of the hybrid AO-OFDM and OS-OFDM architecture. The active InP-based 4-channel IQ modulator PICs are connected with the passive optical transmitter lightwave circuit (glass board) at a common interface. The assembly technique is shown in the picture on the right.

Monolithic Integration of the Transmitter

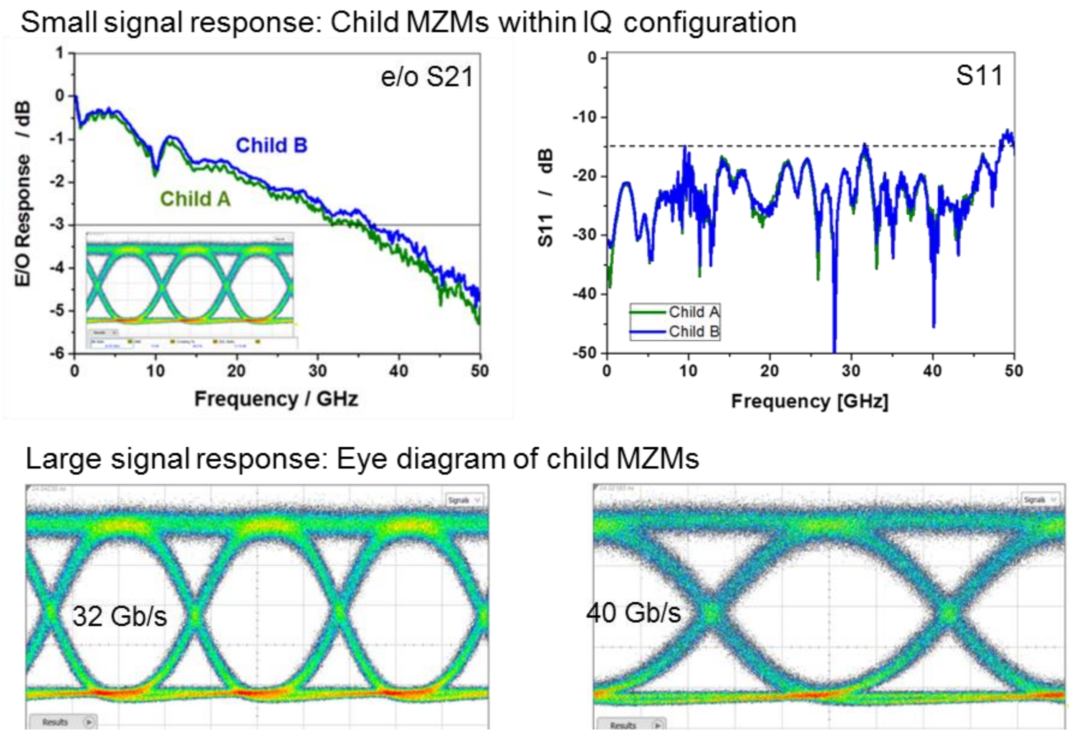
As an alternative transmitter fabrication approach to the hybrid concept, fully integrated 8-channel OFDM/Nyquist-WDM Tx PICs on InP have been designed, fabricated and characterized in WP3. The CAD mask layout and a photograph of a fully integrated 8-channel AO-OFDM InP transmitter PIC is depicted in the figure below.

[2] R. Kaiser, B. Gomez Saavedra, G. Cincotti, M. Irion, P. Mitchell, N. Psaila, G. Vollrath, M. Schell, “Integrated all-optical 8-channel OFDM/Nyquist-WDM transmitter and receiver for flexible terabit networks”, International Conference on Optical Transparent Networks (ICTON) Budapest, Hungary 2015.



Schematic and photograph of a fabricated AO-OFDM Tx PIC integrating a 1x8 optical splitter, eight TWE MZ IQ modulator channels, and an 8-port AWG as main building blocks (right). Integrated monitor photodiodes as well as electrical 50Ω RF termination resistors and specific CPW/CPS transmission lines/transitions are shown on the left.

The integrated MZ modulators (child) within each IQ configuration (parent) have been characterized showing good results. The small signal response characteristics are comparable with those of single standard IQ devices fabricated at HHI for commercial applications.



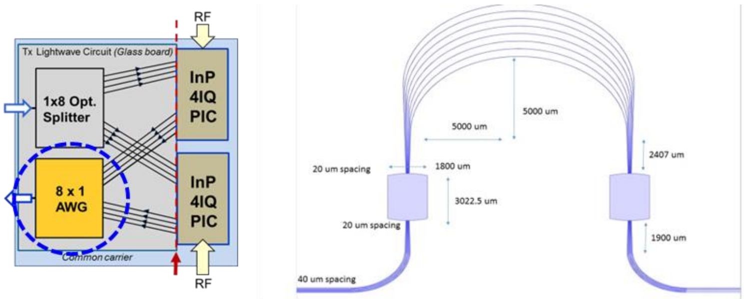
Electro-optical S21 and electrical S11 vs frequency of upper (child A) and lower (child B) MZ modulator in an IQ configuration, and a clear open MZ modulator eye diagram at 40 Gb/s.

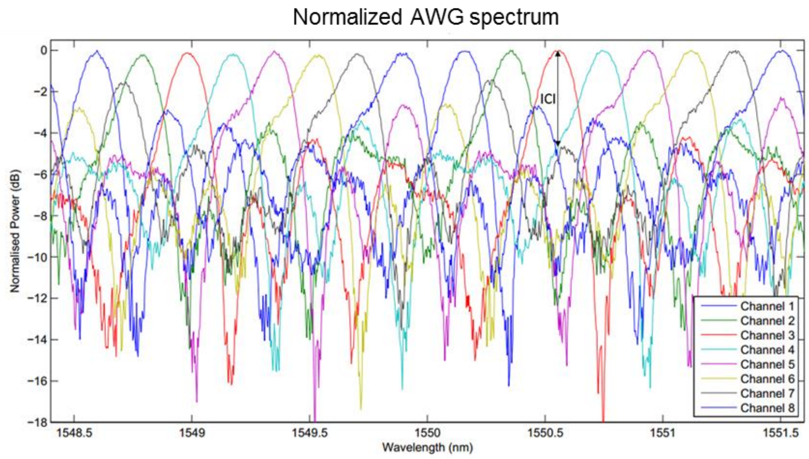
DC/RF performance characteristics (# ATXPIC-7679, 7680)		Target Spec	
Vπ (-5V bias) / V	2.3 ± 0.4 (2.0 ± 0.1)	≤ 3 V	✓
Insertion loss IL / dB	14.8 ± 1.0 (no ref.)	Min.	✓
e/o S21: f(-3dB) / GHz	32 ± 5 (33 ± 4)	≥ 25 GHz	✓
S11 / dB	< -15dB up to 45 GHz	≤ - 10 dB	✓
e/o S21: f(-3dB), **Mod2** /GHz	42 ± 3 -> OS-OFDM Tx PIC!	≥ 35 GHz	✓
Blue numbers: Reference data of single (!) IQ MZ modulator production at HHI			

Comparison of the actual DC/RF performance characteristics of the integrated MZ modulators with the initial ASTRON target specifications

ASTRON transmitter's AWG on glass board

The Arrayed Waveguide Grating (AWG) is the core piece in both basic components of the ASTRON transceiver, transmitter and receiver. The device has 8 inputs and output ports and a free spectral range of FSR=200 GHz. This AWG is monolithically integrated on the transmitter and receiver planar silica (glass) motherboard together with an optical 1x8 power splitter/combiner.



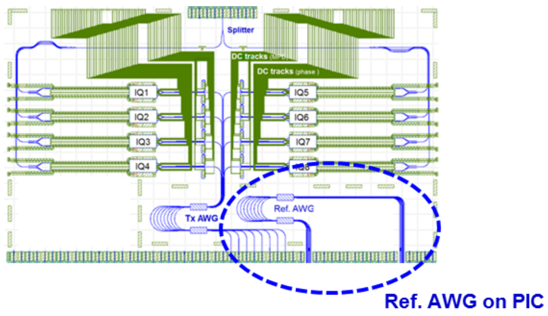


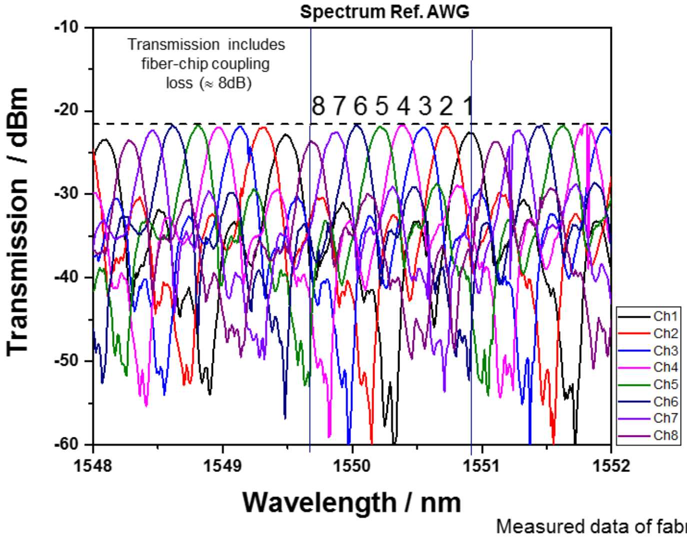
	ASTRON specs	Experim.
Center wavelength / nm	1500	**1500**
FSR / GHz	200	**195**
Channel spacing / GHz	25	**20 … 25**
Excess loss / dB	≤ 12	**21**
Power uniformity / dB	≤ 5	**2**
Crosstalk (ICI) / dB	≥ 12	**2.5 … 5**

8x8 AWG on glass layout and spectrum. The table on the bottom right provides a comparison between the initial ASTRON specs and the ones measured experimentally.

Monolithic 8-port AWG on InP

For the monolithic approach an AWG was designed and fabricated. The AWG layout and the characterization results are presented in the following figures.





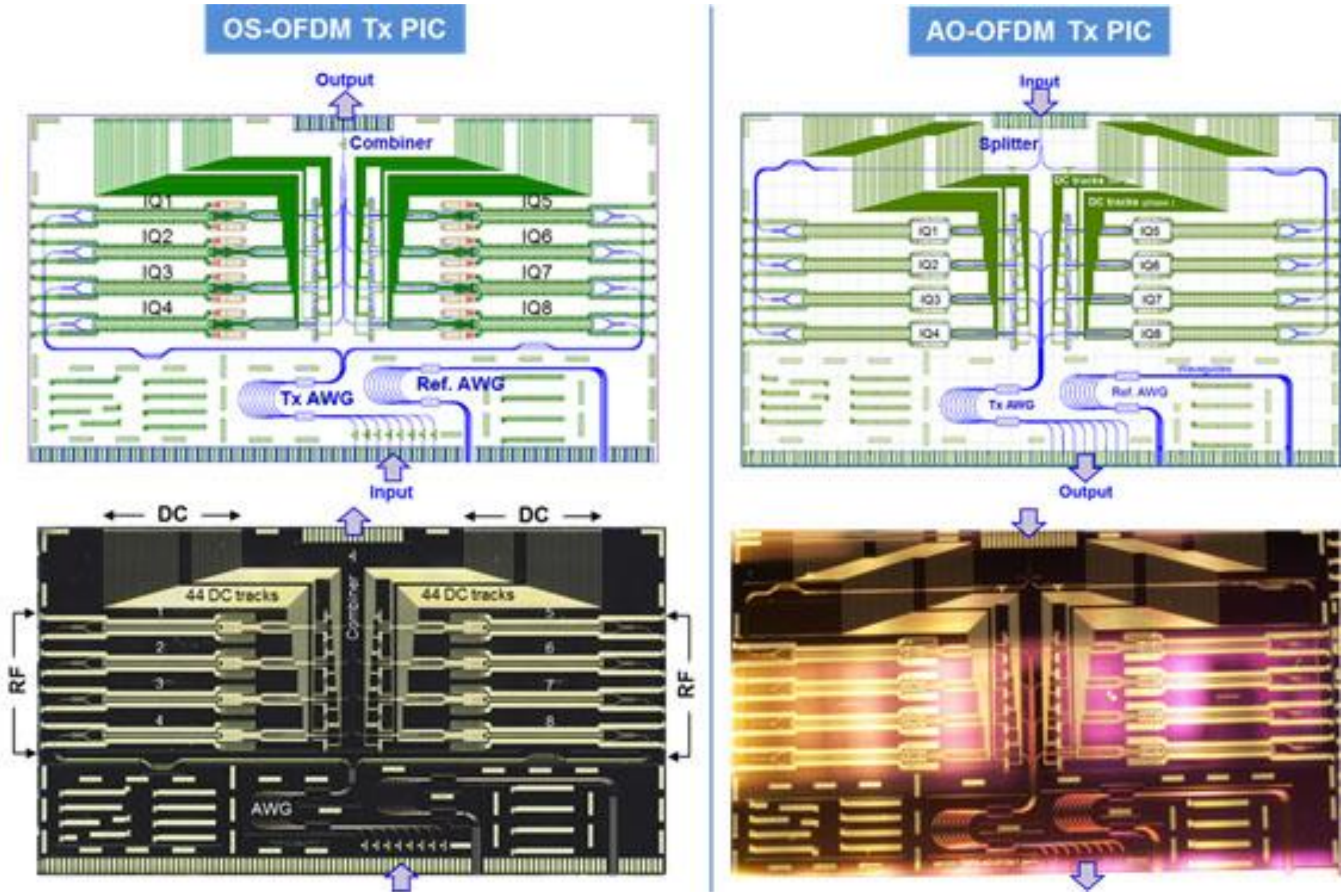
Measured data of fabricated Tx PICs (Wafer# ATXPIC-7679/80)

	ASTRON specs	Theory	Exp. (best)	Exp. (average)
FSR [GHz]	200	200	175.8 ± 1.7	176 ± 5
Channel spacing / GHz	25	25	22.3 ± 1.3	22.5 ± 2.5
Excess loss / dB	≤ 12	≈ 11	14 ± 1	14.3 ± 2.4
Power uniformity / dB	≤ 5	1.3	1.8	1.5 ± 0.3
ICI / dB	≥ 12	25	8.3 … 10.5	7.5 ± 3

8x8 AWG on InP layout and spectrum. The table on the bottom right provides a comparison between the initial ASTRON specs and the ones measured experimentally.

The CAD mask layouts and photographs of the fully integrated 8-channel OS-OFDM and AO-OFDM InP transmitter PICs are depicted in the following figures. This work was presented at ECOC 2016[3].

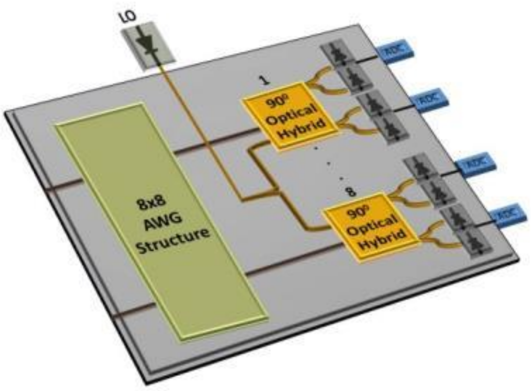
[3] B. Gomez Saavedra, R. Kaiser, J. Beyer, M. Rausch, M. Gruner, W. Fürst, M. Schell, "8-channel InP OFDM Transmitter PIC with Integrated Optical Fourier Transform",ECOC, Düsseldorf, Germany, 2016



Schematic and photograph of a fabricated AO-OFDM Tx PIC integrating a 1x8 optical splitter, eight TWE MZ IQ modulator channels, and an 8-port AWG as main building blocks (right). Integrated monitor photodiodes as well as electrical 50Ω RF termination resistors and specific CPW/CPS transmission lines/transitions are shown on the left.

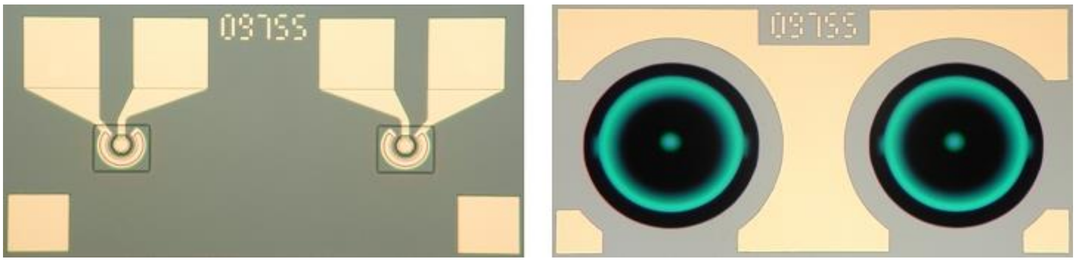
WP4: ASTRON coherent receiver

The Rx PLC consists of a similar 8-port AWG structure that implements the Discrete Fourier Transform (DFT) in order to decode the incoming signals and an array of 90^{o} hybrids followed by balanced Photo-Detectors (PD).

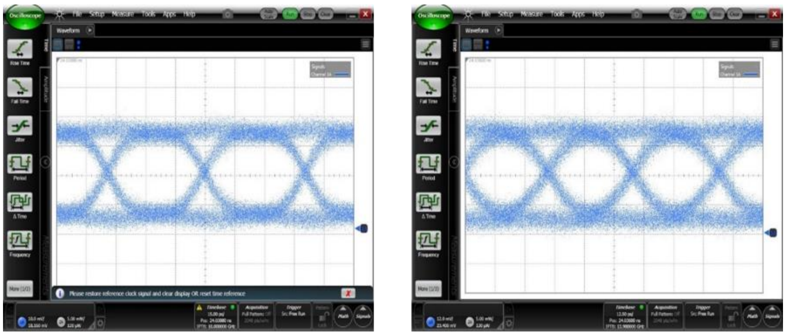


Schematic of the novel integrated multi-channel terabit capacity coherent receiver board

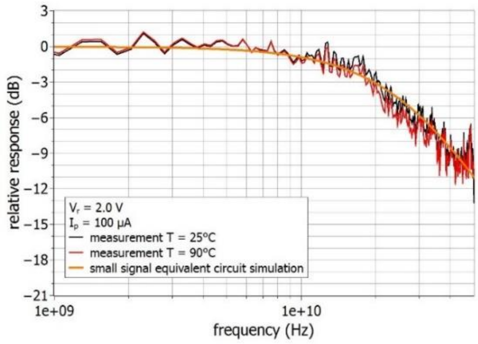
Balanced InP based 25 Gb/s photodiode arrays with a monolithically integrated backside lens and an optimized RF layout were developed as the basic active receiver building block. First samples of the photodiodes have been manufactured and tested. The performance characterization shows that the developed photodiodes are well suited for the ASTRON project application. The next **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**show photographic images of the topside and backside of the manufactured balanced photodiode array as well as the results of their characterisation.



Photographs of the balanced PD array. Left: PD topside. Right: PD backside with integrated lenses.



20 GHz (left) and 28 GHz (right) eye diagram measurements of the Astron Rx single channel test boards.

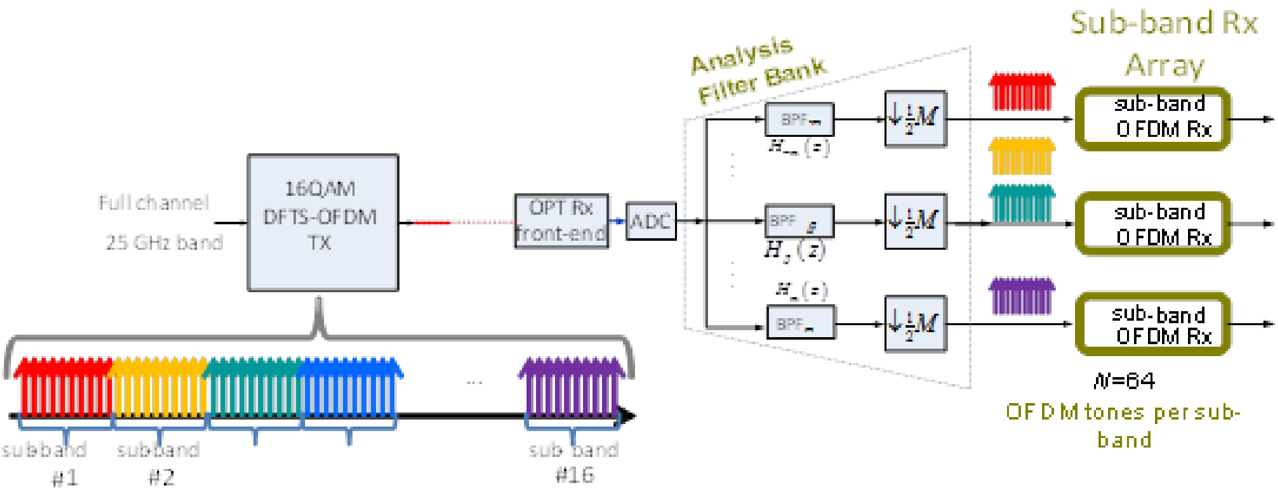


S12 - Frequency response measurements.

WP5 Software defined signal processing, modulation and control

On the DSP[4] and FEC[5] sides, the ASTRON project delivered a set of competitive solutions that maintain good performance, but also offer reduced implementation complexity and power consumption.

The rationale behind the developed filter-bank based OS-OFDM transceiver is to break the digital processing into multiple parallel virtual sub-channels, occupying disjoint spectral sub-bands. The following figure shows a top level view of the DSP algorithmic chain implemented within the OS-OFDM receiver.



The basic diagram of the filter-bank based OS-OFDM DSP.

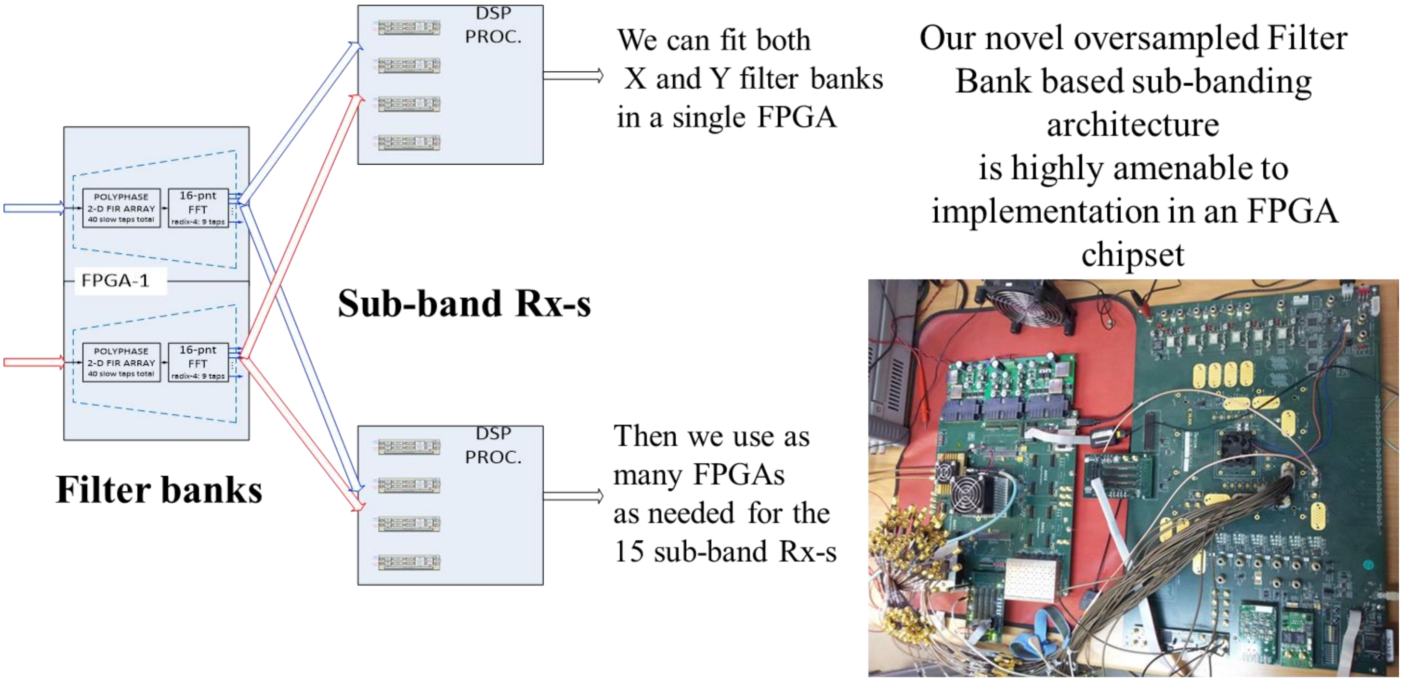
Detailed architectures of the implementation of the OS-OFDM transmitter and the receiver signal processors were delivered. We came up with the design, implementation and testing of the FPGA Digital- to-Analog Converter (DAC)

[4] Moshe Nazarathy and Alex Tolmachev, "Subbanded DSP Architectures Based on Underdecimated Filter Banks for Coherent OFDM Receivers: Overview and recent advances," Signal Processing Magazine, IEEE , vol.31, no.2, pp.70,81, March 2014.

[5] G.Tzimpragos, C. Kachris, I.B. Djordjevic, M. Cvijetic, D. Soudris, and I. Tomkos, "A Survey on FEC Codes for 100G and Beyond Optical Networks", in IEEE Communications Surveys and Tutorials, vol. 18, no. 1, pp. 209-221, 2014

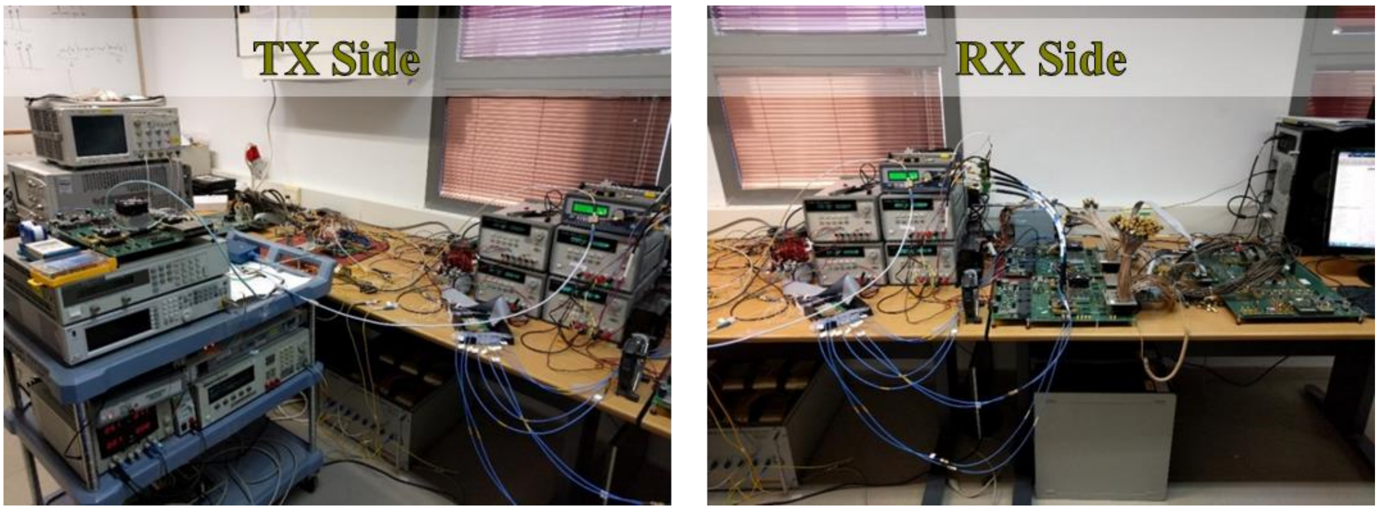
subsystems and the analogue electronics that were used leading to the integration of the sub-system within the ASTRON transmitter. This involved the use of the FPGAs to drive the eight integrated InP IQ modulators at a symbol rate of 28 Gbaud.

The FPGA hardware implementation architecture is shown in the next figure (left figure), while the actual implementation on the FPGAs is shown on the right figure.



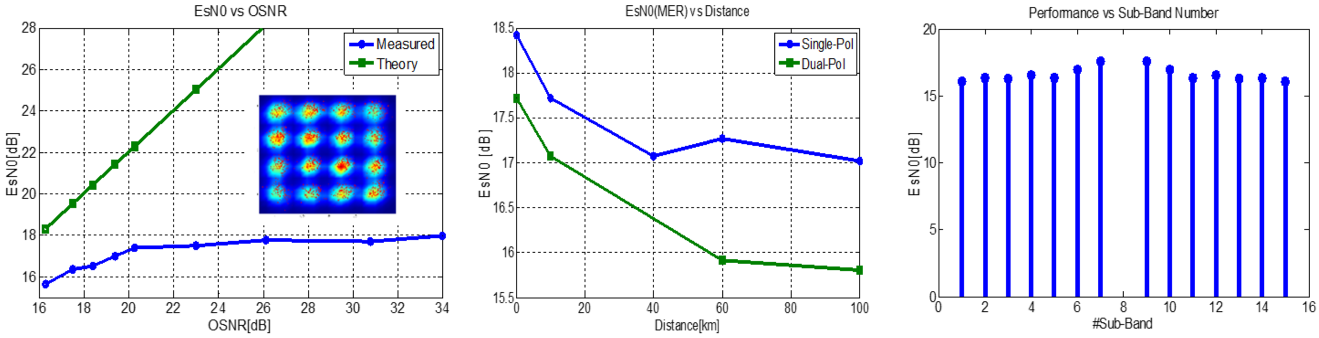
FPGA hardware implementation architecture

The next figure shows the implementation of the ASTRON transceiver (Tx Side on the left and RX side on the right), while it was tested at UCL.



Real-Time setup of the ASTRON transceiver

All receiver functions are real-time implemented resorting to just 3 FPGA chips. FPGA X/Y interfaces to the ADC chips, performs calibration of internal ADC parameters and IQ gain/phase imbalance correction, at system bring-up. Following IQ- imbalance correction, the data is de-multiplexed into sub-bands. Sub-banding is performed on sets of 16 input samples; due to 2x oversampling, a factor-of-8 rate slow-down is attained. To evaluate system performance we measured EVM/EsN0 vs OSNR (next figure on the left). A dominant impairment was identified as quantization noise. The estimated ADC ENOB for both DAC and ADC was ~4bits. In actual measurements, the effective ADC noise was higher due to lack of adaptive pre-ADC AGC stage. The maximally attainable estimated SNR was ~18dB. Beyond back-to-back, the transmission distance was tested over 100 km SMF (next figure on the middle), yielding minor performance loss, mostly due to setup imperfections. Upon using both polarizations (POL) yielded SNR degradation of ~1dB (likely due to dual-POL PAPR). In addition we measured the performance as a function of sub-band number (next figure on the **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** right) and again as expected we see some degradation in performance, mainly due to ADC filter attenuation in all measurements, the tested BER was under the soft FEC 3.8e-3 limit, indicating feasibility for practical optical OS-OFDM implementations at very high spectral and power efficiency.



Experimental results: (left) Measured EsN0 (MER) for various OSNR conditions (middle) Measured EsN0 (MER) vs reach (right) Measured EsN0 (MER) per sub-band (bar-chart) over the various sub-bands (degradation away from center due to ADC/DAC.

In just 3 FPGAs we realize fastest (180 Gbps) real-time filter-bank based OS-OFDM 16-QAM 25 GHz Rx, at record 1.06 samples/symbol (7.3 b/Hz), demonstrating dual polarization SMF transmission[6].

In ASTRON, the OS-OFDM transceiver can adapt to the channels requirements by partially reconfiguring the implemented FEC module. The dynamic reconfiguration is used in order to load the right version of the ASTRON QC-LDPC FEC code based on the code rate and the block size that is required. In our measurements, the reconfiguration time is always less than 12 ms, which means that the proposed scheme could be utilized in flexible optical networks (where the reconfiguration time e.g. for the optical switches is in the order of a few ms)[7].

Table 1. Reconfiguration time for the FEC.

Codeword length (bits)	Block size (bits)	Code rate	Area (LUTs)	Reconfig. Time
648	27	1/2	837	4.0 ms
648	27	2/3	756	3.6 ms
648	27	3/4	675	3.2 ms
1296	54	1/2	1674	8.1 ms
1296	54	2/3	1512	7.3 ms
1296	54	3/4	1359	6.6 ms
1944	81	1/2	2511	12.1 ms
1944	81	2/3	2187	10.6 ms
1944	81	3/4	2025	9.8 ms

[6] A. Tolmachev, M. Meltsin, R. Hilgendorf, M. Orbah, T. Birk, S. Ben-Ezra and M. Nazarathy, "*Real-Time Hardware Demonstration of 180 Gbps DFT-S OFDM Receiver Based on Digital Sub-banding,*" ECOC, Dósseldorf, Germany, 2016.

[7] C. Kachris, G. Tzimpragos, D. Soudris and I. Tomkos, "*Reconfigurable FEC codes for software-defined optical transceivers,*" in Optical Communications and Networks (ICOCN), 2014.