Trials of a Coherent UDWDM PON Over Field-Deployed Fiber: Real-Time LTE Backhauling, Legacy and 100G Coexistence

Harald Rohde, *Senior Member, IEEE*, Erich Gottwald, Sönke Rosner, Erik Weis, Paul Wagner, Yuriy Babenko, Daniel Fritzsche, and Hacene Chaouch

(Invited Paper)

***Abstract*—Transmission capabilities of a coherent real-time UDWDM PON over deployed fibers in two testbeds (Berlin and Darmstadt, Germany) are demonstrated. Extensive coexistence tests including LTE backhauling and GPON, RF-Video, 100G and OTDR were performed. A silicon photonics-integrated CMOS laser was used for parts of the trial.**

***Index Terms*—Communication systems, optical fiber communication, optical modulation.**

I. Introduction

The upcoming NG-PON2 standard series G.989 [1] describes next generation optical access systems. Within this standard, a point-to-point WDM PON overlay is intended to provide connectivity for demanding applications such as mobile backhaul, mobile fronthaul and business applications while residential customers will be connected with a TDM-WDM hybrid system (TWDM).

Coherent Ultra Dense WDM PON (UDWDM PON), as for example described in [2], [3], [4] offers a good match to the requirements for the point-to-point overlay, as described in G.989.1 [1]. This paper presents the first real-time transmission of a coherent UDWDM system over field deployed fiber.

A UDWDM prototype implementation is described (Section II) and its LTE backhauling capabilities are demonstrated over 75 km of deployed fiber in the Deutsche Telekom testbed in Berlin, Germany. Furthermore, its capability to coexist with GPON and 100G WDM transmission systems on the same optical fiber was shown (Section V).

In a subsequent field trial in another Deutsche Telekom testbed in Darmstadt, Germany, the commercial narrow linewidth tunable downstream laser in one OLT was replaced by the prototype of a silicon photonics (SiP) integrated CMOS laser [5] (Section IV). Successful coexistence measurements with a legacy GPON system, an analogue RF video overlay and an OTDR system simultaneously on the same fiber were performed. No degradation in transmission performance was measured due to either the use of the SiP laser or the presence of the coexisting systems.

This paper is an extended version of [6].

II. Real Time UDWDM Setup

The setup of the coherent UDWDM system is shown in Fig. 1. The OLT consists of 3 Optical Transceiver Groups (OTGs) each of which transmits up to 10 wavelengths and receives one wavelength. The restriction to only one received wavelength was implemented due to the limited sample rate of the receiving ADC; simultaneous transmission and reception functionality of up to 9 wavelength, using the same principle, has been demonstrated in [7]. This paper concentrates on the downstream properties of the system, upstream results have been shown e.g. in [3]. The central frequencies of the OTGs are separated by 50 GHz while the individual wavelengths transmitted by the OTGs are separated by 2.799 GHz. Each wavelength transports 1.244 Gbit/s. The modulation format is root raised cosine pulse shaped ($\alpha = 0.5$) DQPSK, resulting in a baud rate of 622 Mbaud, and the framing structure is OTU 0.

The payload is either a 1 Gbit/s Ethernet signal or a PRBS 15 sequence. For each of the 10 wavelengths, the OTGs contains a framer unit, an forward error correction (FEC) encoder and a digital up-conversion stage which converts the digital baseband signals to digital RF carriers. The output signals of all 10 digital up-conversion stages are then added and sent to a pair of 60 GSamples/s DACs. The pair of DACs drives an IQ modulator which modulates the 10 wavelengths using a single continuous-wave laser source

The signals of the OTGs are then combined by a passive splitter and amplified by an EDFA. After transmission over various fiber distances, the signals are split by another passive

Manuscript received August 13, 2014; revised December 5, 2014; accepted December 22, 2014. Date of publication January 15, 2015; date of current version March 4, 2015. This work was supported by the German Ministry of Education and Research (BMBF) under the Projects ATOB (FKZ: 16BP1037) and NGOA (FKZ: 16BP1040).

H. Rohde, E. Gottwald, and S. Rosner are with Coriant GmbH, 80240 Munich, Germany (e-mail: Harald.Rohde@coriant.com; erich.gottwald@coriant.com; Soenke.Rosner@coriant.com).

E. Weis is with Deutsche Telekom AG, Innovation Laboratories, 10781 Berlin, Germany (e-mail: Erik.Weis@telekom.de).

P. Wagner and Y. Babenko are with Deutsche Telekom AG, 64295 Darmstadt, Germany (e-mail: Paul.Wagner@telekom.de; Yuriy.Babenko@telekom.de).

D. Fritzsche is with BISDN GmbH, 10785 Berlin, Germany (e-mail: Daniel.Fritzsche@bisdn.de).

H. Chaouch is with Skorpios Technologies Inc., Albuquerque, NM 87111 USA (e-mail: hacene_chaouch@skorpiosinc.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2015.2392154

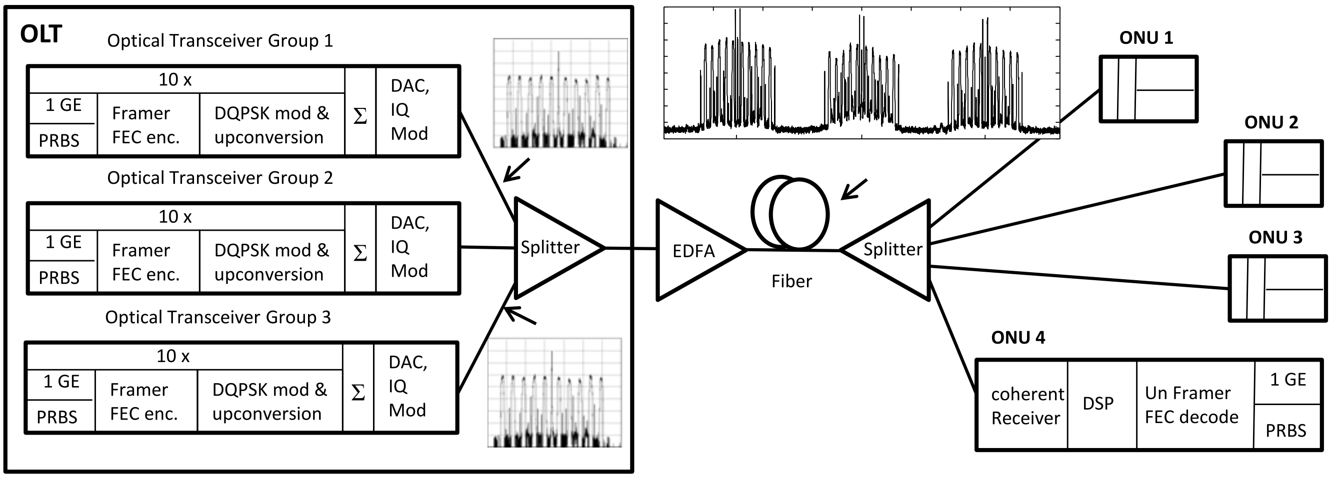

Fig. 1. Real time UDWDM system setup for downstream transmission. The insets show indicative transmit spectra at the output of the OTGs and the spectrum in the fiber. Up to 30 wavelengths were transmitted.

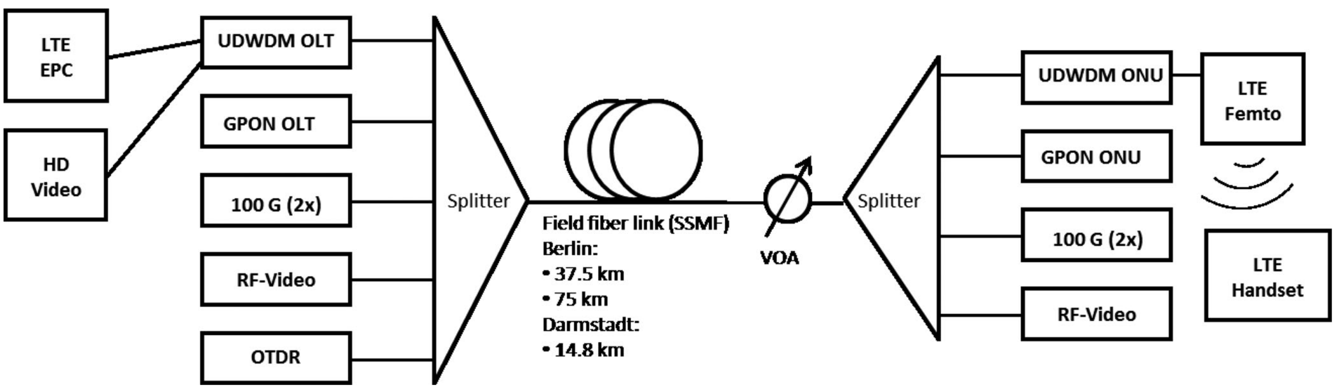

Fig. 2. Generic field trial setup. Not all legacy services were always present due to limited availability at the test sites.

splitter and received by 4 ONUs. Each ONU contains a polarization diversity coherent heterodyne receiver, a DSP unitwhich generates the bit stream out of the received digital samples, a de-framing unit and an FEC decoder. The use of FEC is configurable: the BER curve in this paper was measured without FEC, while the high-definition (HD) video transmission and the LTE backhauling experiments were done with an active FEC. The system has been described in more detail e.g. in [2] and [3].

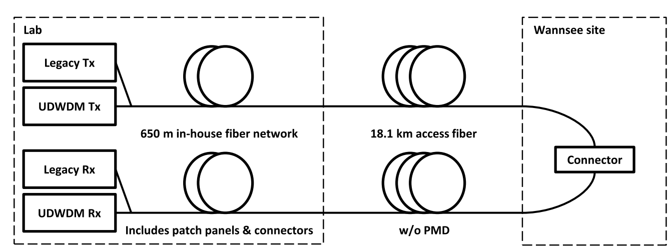

Fig. 3. Setup of the Berlin testbed: single loop including in-house and access fibers.

III. Field Trial Testbed Setup

The generic field trial test set-up is shown in Fig. 2. In addition to the UDWDM signals, several other signals from other optical communication systems were fed onto the single mode fibers in order to prove the coexistence capabilities. Two field trials were performed on two different testbeds of the Deutsche Telekom in Berlin and Darmstadt, Germany, respectively. This section summarizes the setup, and detailed results are given in Section V.

The Berlin testbed offered a realistic passive optical network (PON) environment with multiple patch panels, connectors and splices. This includes an in-house fiber network of approximately 650 m length as well as several deployed access fiber links from the laboratories in central Berlin to a site in the outskirts of Berlin (Wannsee, all SSMF). The fibers at the remote Wannsee site were patched in order to form fiber loops with a single loop length of 37.5 km, including in-house fiber (Fig. 3). No amplification was introduced in the remote site. The deployed fibers differed in age and properties. The basic loop had negligible PMD and an attenuation of about 15 dB including connectors and represented the standard PON scenario used for basic and co-existence tests. A second loop had a very high PMD of 80 ps and a high attenuation of about 20 dB and was used as an experimental scenario to show the transmission capabilities of the UDWDM system. The Darmstadt site offered a field deployed SSMF fiber link of 14.8 km length and a Silicon Photonics CMOS laser [5] for downstream transmission.

The testbed setups were used to demonstrate the following test cases: (1) to show the transmission of UDWDM signals over field deployed fiber for the first time, (2) to demonstrate the coexistence of UDWDM with legacy systems on the same fiber and finally, (3) to show the suitability of high performance SiP CMOS lasers for such a system. The UDWDM system transmitted either PRBS test data for BER measurements, real time HD Video payload or real time LTE backhauling data. For the coexistence measurements, GPON, 100G WDM and LTE were available at the Berlin site, while the Darmstadt site offered GPON, RF-Video and OTDR.

As for the Berlin GPON system, we used commercially available ONU/ONT (class B+) on the 15 dB loop and a 1:4 power-splitter so that power budget was not a limiting factor. The 100G WDM system was also a commercial one which provided two tunable 100G channels on a 50 GHz grid in the C-band. The system used digital coherent signal processing as well as FEC and optical amplification at the receiver. During the tests, the 100G channels were tuned very close to the UDWDM signal. The optical power of the 100G channels as well as the additional control channels were automatically set by the system. The client side signals for both, GPON and 100G WDM, were coming from an Ethernet/packet tester.

Many FTTx deployments also use a RF Video overlay in order to provide non-IPTV video services to their customers. Coexistence with those RF Video systems is essential and therefore UDWDM and RF-Video were sent over the same fiber at the Darmstadt test site. The RF Video system was a mixed analog and digital system, occupying channels from 86 MHz to 866 MHz.

IV. Silicon Photonics CMOS Laser

One of the novelties in the Darmstadt trial was the use of an integrated tunable silicon photonics laser [5], [8], [9] for downstream transmission. The key feature of this laser is the seamless embedding of the active III-V material into the CMOS die. This laser is fabricated in a standard CMOS foundry. There are three major phases involved in the fabrication process of this laser: The front end of the line (FEOL), the middle of the line (MOL) and finally, the back end of the line (BEOL). The FEOL consists of the definition of all passive and active silicon regions as well as the receptor sites for bonding of the unprocessed III-V gain material. The MOL includes three major steps: bonding the gain material into the receptor sites, building the integrated coupler between the silicon and III-V regions, and last, self-alignment of the gain and coupler waveguides. Finally the BEOL forms all contact layers, such as vias and metal traces to the FOEL and MOL devices. These contacts are needed for the gain section current injection as well as gratings, and phase elements heaters control. The BOL also seals the III-V material, removing he requirements for the hermeticity of the package. As shown in Fig. 4, tuning is performed by means of integrated heaters that vary the gratings and phase section index of refraction through the thermo-optic effect. The gratings form a ‘Y’ structure, thus the Vernier effect is used for setting the required wavelength.

The light-current (L-I) measurements of the SiP CMOS laser were performed while having the device mounted on a temperature-controlled bench, allowing characterization at

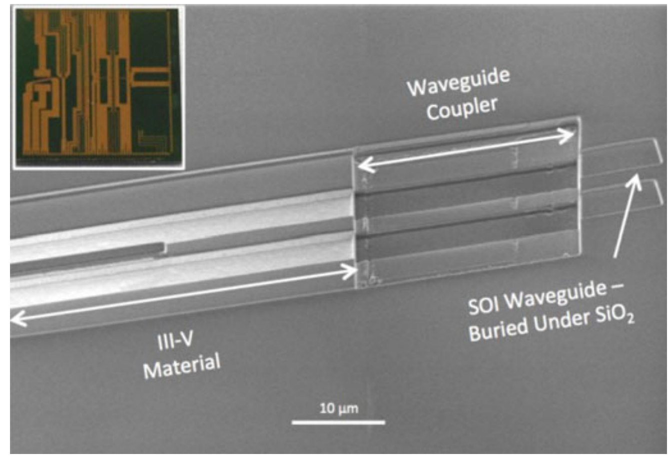

Fig. 4. SEM image of the III-V chip embedded in silicon with the coupler waveguide to the SOI region. Inset illustrates a completed CMOS laser.

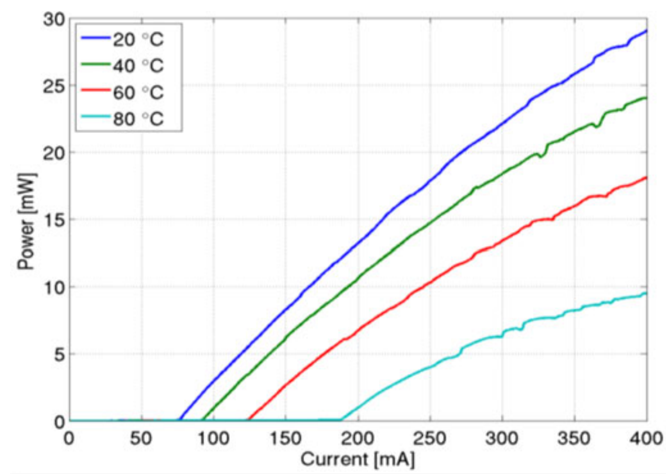

Fig. 5. CW L-I curves at different ambient temperatures.

variable temperatures. Fig. 5 shows the continuous wave (CW) L-I curves at several temperatures, measured with an integrating sphere detector. It should be noted that no control loops were implemented on the tuning heaters while performing these measurements. In addition, the main cavity heater was not used, resulting in some misalignment between the cavity longitudinal modes and the gratings reflection peaks consequently yielding suboptimal output power. As the main cavity phase section was not actively controlled, mode hopping is observed along the L-I curves. A slope efficiency of 0.125 W/A was measured at 20°C. The low thermal impedance of 21 °C/W allows laser action at temperatures as high as 80 °C, with an optical output power of about 10 dBm. It is important to note finally that the relatively high threshold currents presented in Fig. 5 are mainly due to an initial over designed III-V gain section length yielding larger photon absorption, significantly contributing to the overall cavity losses. Subsequent laser designs incorporate III-V gain sections that are fine-tuned in length to the cavity mirrors’ reflectivities, without inducing any significant extra losses.

In Fig. 6, an example of the CMOS laser optical spectrum is shown with an injection current to the gain section of 120 mA. In this condition, approximately 6 dBm of output power is emitted at 191.75 THz. As the laser Y branch grating structure allows for

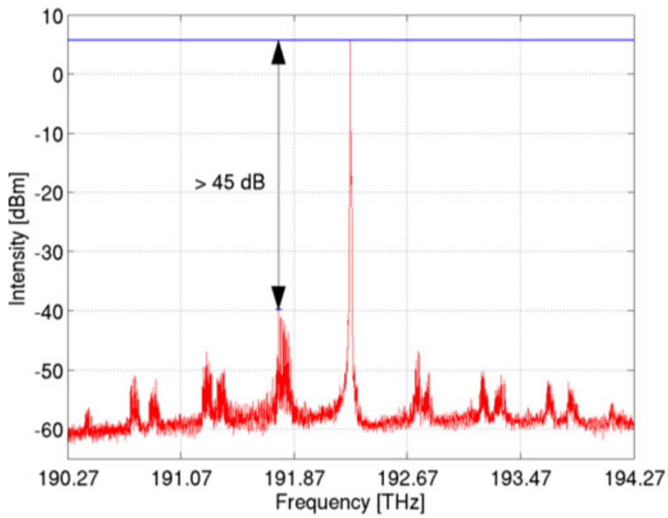

Fig. 6. CMOS laser spectrum at 120 mA pump current and corresponding side mode suppression.

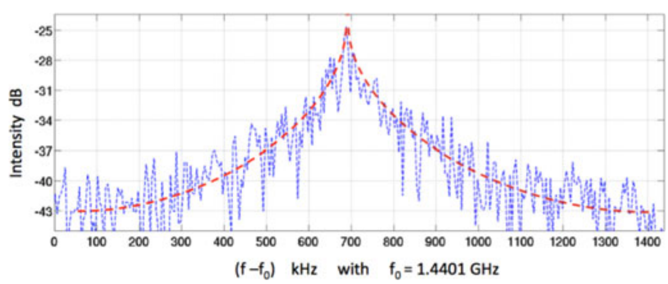

Fig. 7. Beating spectrum of the integrated CMOS laser and a narrow linewidth commercial tunable laser.

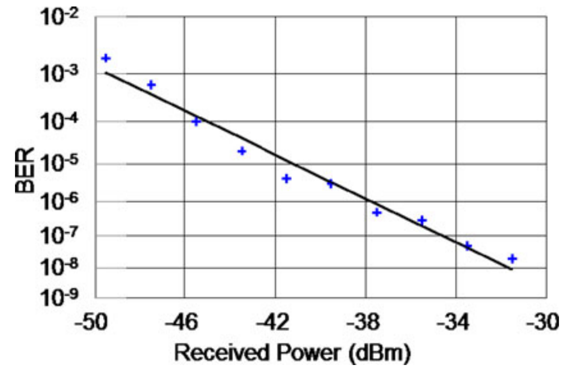

Fig. 8. ONU Receiver BER Curve.

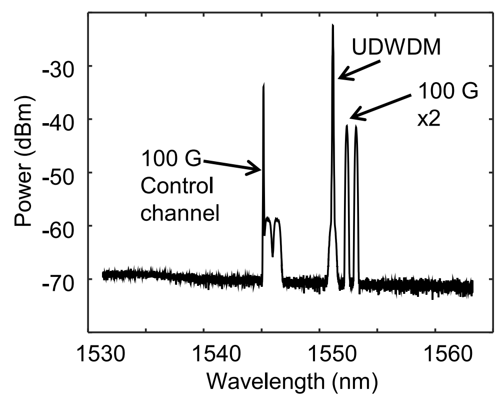

Fig. 9. 100G coexistence spectrum.

a high ratio of the wanted main mode versus the side modes, the laser achieves an overall side mode suppression ratio (SMSR) of more than 45 dB, which is perfectly applicable for the testes UDWDM system.

Linewidth is an extremely important characteristic of semiconductor tunable lasers specifically when employed in coherent systems. Phase-encoded multilevel schemes such as DP-QPSK, 16-QAM or 64-QAM can be strongly affected by the employed lasers' phase noise. In the following, we perform a heterodyne measurement of the CMOS laser linewidth. This experiment was not part of the field trial but it offers valuable insight into the feasibility of such a laser for the field trial and is therefore mentioned here. In this experiment, the laser was mixed with a narrow-linewidth reference commercial laser. The resulting RF beating signal was sampled with a fast oscilloscope over an adequate time window, and the fast Fourier transform of the discrete signal was taken. An example of the measured power spectral density of the beating signal is shown in Fig. 7. The result consists of the combined Lorentzian linewidths of the two lasers; hence, we estimated the linewidth of the CMOS laser to be below 100 kHz. This constitutes a further improvement to the already good linewidth results previously reported [5] and proves suitability for long haul or multilevel-phase-encoded metro coherent applications [8].

V. Results

As an example for the performance of real time transmission of UDWDM over a field fiber, an ONU receiver BER curve from Darmstadt is shown in Fig. 8; the sensitivity at the FEC threshold of BER $= 10^{-3}$ is about -49 dBm. These measurements were performed with deactivated FEC. UDWDM central wavelength was around 1530 in this case, in order to avoid collisions with the RF-Video. The launch power was -3 dBm per wavelength. The fiber length was 14.8 km.

Back to back measurements were also performed in both testbed locations. No sensitivity degradation due to the influence of the fiber could be observed in neither testbed within the limits of the measurement inaccuracy.

Further tests concentrated on coexistence verifications. Fig. 9 shows the spectrum of an UDWDM system, operating over the same field deployed fiber (Berlin) together with two wavelengths from a commercial 100 G WDM transport system. The signals in all coexistence scenarios were combined by passive splitters. The single UDWDM wavelengths are not resolved in this scale. The two 100 G wavelengths ($\sim$1553 nm) are separated by 100 GHz, The UDWDM wavelengths (1551.15 nm) were 150 GHz away from the first 100 G wavelength. The 100G control channel was 750 GHz away, as shown in the figure. The UDWDM launch power was -3 dBm/wavelength (i.e. $+7$ dBm in total). The 100 G launch powers have been automatically set by the 100 G system and are not directly accessible; the

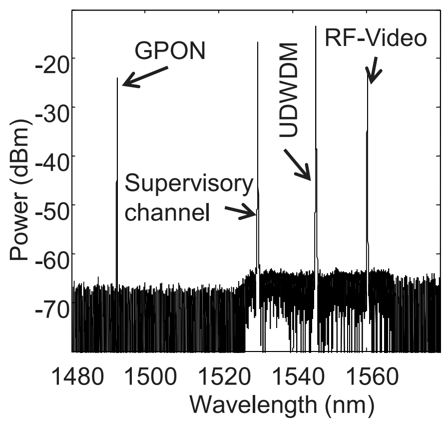

Fig. 10. GPON and RF Video coexistence spectrum.

figure just shows the spectral positions and no absolute powers. No impact could be observed, neither from the 100G onto the UDWDM system or vice versa.

In the Darmstadt test site, coexistence measurements were performed with GPON, RF-Video and an OTDR system, all running over the same field fiber. The spectrum in the fiber is shown in Fig. 10 (OTDR at 1640 nm is not shown). An additional amplifier supervisory channel at 1530 nm was also present. That channel was part of the link and could not be switched off. Again, no impact of any system onto UDWDM could be observed, as well as any impact from UDWDM onto other systems

As the receiver filters of the RF Video systems are quite broadband (about 7 nm, the exact specification is unknown), a degradation of the RF Video BER was observed when the UDWDM wavelength was moved into the RF Video reception window. When the UDWDM wavelength was outside the RF reception window, no deteriorating effects, e.g. due to Raman nonlinearity, could be observed

At the Berlin site, the UDWDM system was used to backhaul an LTE femto base station to its Evolved Packet Core over the Ethernet link that the UDWDM system provided. The fiber distance was 75 km (double loop). As expected for an error free Ethernet backhauling link, no impact onto the LTE transmission link could be observed, any potential delay and jitter addition was below the resolution threshold of the measurement equipment.

A Silicon Photonic integrated CMOS tunable laser was used at the Darmstadt site for the transmission experiments. When comparing the test results with a market-leading InP tunable laser, no difference of transmission performance could be detected.

VI. Summary

A prototype of a coherent UDWDM PON system was tested for the first time over field deployed fiber in two different Deutsche Telekom testbeds in Germany. The receiver sensitivities for back-to-back and over the testbeds were identical.

The suitability of a coherent UDWDM system for LTE backhauling has been proven. Any potential increase of jitter or delay was below the resolution of the LTE measurement equipment; therefore, no additional delay or jitter could be measured.

Coexistence with legacy systems such as GPON, RF-Video, 100G and OTDR measurement equipment has been demonstrated. Neither was the UDWDM transmission influenced by any legacy system nor did the UDWDM influence any of the legacy systems when the UDWDM wavelengths were outside the respective legacy filter bands. Tunable lasers and the potential to use a filter less architecture provide full spectral flexibility.

The demonstrated system operates in the C-Band, which is compliant with the expanded spectrum case of the emerging G.989 standard. Even though not experimentally tested due to the lack of components, the authors expect that this technology can also operate in the L band in order to coexist with TWDM in the shared spectrum case. Coherent UDWDM therefore supports the NG-PON2 point-to-point overlay requirements for pure power-splitter based optical distribution networks.

An integrated Silicon Photonics CMOS tunable laser was used in parts of the experiments and no performance degradation in comparison with a best in class InP tunable laser could be observed.

References

[1] ITU-T G.989 series recommendations.

[2] S. Smolorz, E. Gottwald, H. Rohde, D. Smith, and A. Poustie, "Demonstration of a coherent UDWDM PON with real time processing," in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2011, pp. 1–3.

[3] H. Rohde, E. Gottwald, A. Teixeira, J. D. Reis, A. Shahpari, K. Pulverer, and J. S. Wey, "Coherent ultra dense WDM technology for next generation optical metro and access networks," *J. Lightw. Technol.*, vol. 32, no. 10, pp. 2041–2052, May 2014.

[4] H. Rohde, E. Gottwald, P. Alves, C. Oliveira, I. Dedic, and T. Drenski, "Digital multi wavelength generation and real time video transmission in a coherent ultra dense WDM PON," in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2013, pp. 1–3.

[5] E. Marchena, T. Creazzo, S. B. Krasulik, P. Yu, D. Van Orden, Y. Spann, C. Blivin, J. Dallesasse, J. Varangis, R. Stone, and A. Mizrahi, "Integrated tunable CMOS laser for Si photonics," in *Proc. Opt. Fiber Commun. Conf. Expo.*, 2013, pp. 1–3.

[6] H. Rohde, E. Gottwald, S. Rosner, E. Weis, P. Wagner, Y. Babenko, D. Fritzsche, and H. Chaouch, "Field trials of a coherent UDWDM PON: Real-time LTE backhauling, legacy and 100 G coexistence," in *Proc. Eur. Conf. Opt. Commun.*, 2014, pp. 1–3.

[7] F. Frey, R. Elschner, C. Kottke, C. Schubert, and J. K. Fischer, "Efficient real-time implementation of a channelizer filter with a weighted overlap-add approach," in *Proc. Eur. Conf. Opt. Commun.*, 2014, pp. 1–3.

[8] H. Chaouch, E. Marchena, J. Spann, H. Cai, H. Potluri, J. Zyskind, S. Krasulick, A. Vigloenzoni, G. Bruno, M. Camera, and A. Tartaglia, "High power narrow linewidth, low noise, integrated CMOS tunable laser for long haul coherent applications," in *Proc. Eur. Conf. Opt. Commun.*, 2014, pp. 1–3.

[9] E. Machena, M. Camera, G. Bruno, H. Chaouch, S. Albanna, H. Cai, C. Blivin, L. He, J. Zyskind, S. Krasulick, A. Tartaglia, A. Mizrahi, and R. Stone, "488 Gbit/s DP-16 QAM transmission using integrated tunable CMOS laser sources," in *Proc. Opt. Fiber Conf.*, 2014.

Harald Rohde received the Ph.D. degree in physics from the University of Innsbruck, Innsbruck, Austria, in 2001. Since then, he worked in different departments of the Siemens AG, Nokia Siemens Networks and Coriant. He worked on research for optical transmission systems, covering a broad range of topics. His main interest includes next generation optical access networks. He is author or coauthor of some 70 publications and holds more than 50 patents. He is actively involved in the standardization forum FSAN since 2008.

Erich Gottwald received the Dr. rer. nat. degree in physics. He joined Siemens Central Research Labs for Communication Technology in 1985. In the late eighties, he worked on coherent optical transmission systems and optical measurement techniques. With the up-coming of EDFAs, he switched to WDM systems in 1991 and, as suitable commercial simulation tools were not available at that time, developed a simulation tool for nonlinear fiber optical transmission systems. Besides that he was engaged in analogue video transmission and ultra-high data rate transmission. In the last years, he was engaged in coherent networks with ultra-dense channel spacing and system simulations.

Sönke Rosner joined Siemens HW-/SW-Development Department for Transmission Technology in 1984 after his university graduation in applied science. Since then he worked as SW-Developer, System Engineer and Solution Architect in different departments at Siemens, Nokia Siemens Networks and Coriant R&D. In the last years, he worked as Project Manager for SW/HW development of the Next Generation Optical Access Innovation Project and finally at the Product Architecture of the High Density Wavelength Division Multiplexing Project.

Erik Weis received the Dipl.-Ing. in electrical engineering from the Technical University of Dresden, Dresden, Germany. After joining Deutsche Telekom AG in 1997, he was mainly concerned with the development of access network evolution strategies. In 2009, he joined Deutsche Telekom Laboratories where he works as Project Manager of national and international R&D projects on optical access networks. His current research interests include the fields of next-generation access network design and fixed-mobile network convergence.

Paul Wagner received the Diploma of advanced studies in electronics from the University of Nantes, Nantes, France, in 1995, after the Dipl.Ing. from ISFATES, Saarbrücken, Germany. Since then he was with Deutsche Telekom, Darmstadt, Germany, working in the labs on the early qualification of most diverse fiber-based technologies as WDM and GPON but with escapades in the radio domain as Wimax and Docsis/RfO. He is strongly involved with innovative tests and demos such as coherent transmission and NextGen Optical Access.

Yuriy Babenko received the Eng. degree from the Siberian State University of Telecommunication and Information Sciences, Novosibirsk, Russia, and the Dipl.-Ing. from the University of Applied Sciences, Leipzig, Germany, in 2009. From 2009 to 2014, he was with Deutsche Telekom AG, Darmstadt, Germany, working on the introduction of access technologies such as DSLAM and GPON. Since 2014, he is focusing on data-center architectures for carrier-grade services.

Daniel Fritzsche received the Dr.-Ing. in electrical engineering from the Dresden University of Technology, Dresden, Germany, in 2010. From 2004 to 2008, he was with Deutsche Telekom AG, Berlin, Germany, working on design and modeling of robust optical networks using equalization technologies. From 2009 to 2013, he was with EICT GmbH, Berlin, as Project Manager and Network Architect being responsible for the field of next generation optical access and core networks. In 2012, he cofounded BISDN GmbH, a Berlin-based start-up focusing on research and development of software and appliances for software-defined networks (SDN). Since 2014, he is full-time at BISDN focusing on SDN architecture in fiber-optic communication systems and SDN controller design. He has authored or coauthored more than 40 publications.

Hacene Chaouch received the M.S. and Ph.D. degrees from the University of Arizona, Phoenix, AZ, USA. He also received an engineering diploma from the Paris Institute of Technology's IOGS, Paris, France. Since then, his study has mainly focused on 40, 100 and 400 Gb/s DP-QPSK coherent systems. He has been a key technical contributor with Mintera and Opnext (both acquired by Oclaro) and lately with Skorpios Technologies where he focuses on enabling silicon photonics for both telecom and datacom applications. Among other achievements, he has led the control of the first ever-fabricated CMOS-integrated tunable laser.