Coherent UBL measured with external cavity laser (ECL) as local oscillator at the receiver

Coherent UBL measured

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Authors:
Joerg Pfeifle and Christian Koos (KIT), Vidak Vujicic, Regan Watts and Liam Barry (DCU),
Nicolas Chimot, Francois Lelarge (III-V lab), Kamel Merghem and Abderrahim Ramdane
(CNRS)

Institution:
KIT, DCU, III-V Lab, CNRS
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2 Summary

In view of D3.2 we have performed several experiments using a coherent detection scheme with an external cavity laser (ECL) as local oscillator (LO). The optical sources for these experiments are a gain-switched comb source built from discrete components to have a direct access to tuning the free-spectral range as well as the center frequency. We perform several experiments using different comb line spacings, modulation formats and symbol rate to maximize the data throughput and spectral efficiency. We achieve an aggregate net data of up to 1.867 Tbit/s for transmission over 300 km of standard single-mode fiber (SSMF). This transmission scheme uses a line spacing of 12.5 GHz, a symbol rate of 12 Gbd and 16 state quadrature amplitude modulation (16QAM) on the stronger center carriers and quadrature phase shift keying (QPSK) on the weaker outer comb lines.

Additionally we also tested the suitability of the first generation of MLLD for coherent data transmission with an ECL as LO. Using the feed-forward heterodyne phase noise reduction scheme we obtain a number of 29 lines from a QD-MLLD that allow coherent data transmission of a QPSK signal over 75 km SSMF achieving an aggregate net data rate of 0.971 Tbit/s. This experiment shows that the limiting part of using MLLD for coherent data transmission is indeed the optical linewidth. This challenge however can be well handled for the further course of the project. First the optical linewidth requirements are inverse proportional to the symbol rate used. For future experiments we will be able to use higher symbol rates using the upgraded transmitter technology that will be implemented within Task 3.2.2. A second possibility would be the use of the optical phase locked looped (OPLL) that is being developed within Task 2.4.2.

3 Coherent UBL using a GSCS and an ECL as LO

3.1 Implementation of the GSCS

Figure 1(a) shows the experimental setup of the GSCS. Gain switching is achieved by driving a distributed feedback (DFB) slave laser diode with a large sinusoidal signal (24 dBm) at a frequency that corresponds to the desired line spacing, in combination with a DC bias current of approximately four times the threshold current ($I_{th} \approx 12.5$ mA). Additionally, a master laser (Agilent N7711A) injects continuous-wave light into the slave laser via a polarization controller (PC) and an optical circulator. The master laser establishes coherence between subsequent pulses and transfers its characteristically low optical linewidth (80 kHz) to the individual modes of the comb [1, 2], and reduces the RIN of the comb modes [3]. The comb’s center wavelength can be tuned by simultaneously adjusting the emission wavelength of the master laser and the temperature of the DFB slave. The polarization controller is used to align the polarization state of the injected light with that of the slave laser mode. By carefully selecting the wavelength detuning and the injected power, long-term (during several days) operational stability of the GSCS can be achieved. The GSCS operates without automated feedback control, and without need for manual adjustment of detuning and polarization. In our experiments, the injection power is set to approximately 7 dBm, and the slave laser is temperature-controlled at 25 °C.
Fig. 1. (a) Setup schematic of the GSCS. A frequency comb is generated by gain switching of the DFB slave laser. The line spacing is determined by the frequency of the RF drive signal. By injecting light from the master laser to the slave laser via a circulator, the low linewidth and RIN of the master laser are transferred to the comb lines. (b–d) Comb spectra (blue, left axis) measured at position “Comb output” with a line spacing of (b) 20 GHz, (c) 18.5 GHz, and (d) 12.5 GHz (RBW 20 MHz) and optical carrier-to-noise density ratio (OCNR – black, right axis) for the comb lines used for the data transmission experiments.

We investigate the GSCS with three different line spacings, 20 GHz, 18.5 GHz and 12.5 GHz, by appropriately changing the frequency of the RF synthesizer. The respective GSCS spectra are depicted in Figs. 1(b)–1(d) on the left-hand axis (blue). The power levels correspond to the actual power of the comb measured at position “Comb output” in Fig. 1(a). The total power in all three cases amounts to +3.5 dBm. On the right-hand axis of Figs. 1(b)–1(d) we depict the optical carrier-to-noise density ratio (OCNR) of the comb lines that are used for the data transmission experiments. The OCNR is defined by the ratio of the power of the unmodulated carrier to the underlying noise power in a spectral bandwidth of 1 Hz. Note that some authors use a reference bandwidth of 0.1 nm for evaluating the noise power. An OCNR value of 125 dB Hz corresponds to an OCNR (by some authors named OSNR) of approximately 24 dB, when measuring the noise in a reference bandwidth of 0.1 nm as done, e.g., in [4,5]. The origin of the noise floor in the GSCS spectra is discussed in [6], where the trade-off between flatness and high-frequency FM noise was elaborated. Here, we concentrate on “flat combs” [6], accepting the noise penalty in favor of a higher number of sub-channels and hence higher aggregate data rates.

Note that the optical bandwidth of all three combs in Figs. 1(b)–1(d) is the same. The bandwidth is dictated by the intrinsic dynamics of photons and electrons within the slave laser. Choosing a smaller line spacing will yield a larger number of lines. Note that the current setup for comb generation comprises discrete components. Further cost and complexity reduction as well as a stability improvement can be obtained by a monolithic integration of master and slave lasers [7].

3.2 Super-channel generation and characterization
For a given line spacing, super-channel capacity is dictated by two parameters: First, the number of carriers that can be derived from the comb source, which defines the number of sub-channels, and second, the power levels and OCNR of the respective carriers that determine the modulation formats to be used on each sub-channel provided that the carrier linewidth is sufficiently low. As a matter of fact, the comb line power is highest in the center of the GSCS spectrum and decreases towards the periphery. In practical transmission systems, however, equal power distribution among all involved sub-channels is desired. This requires attenuation of the center comb lines relative to the power of the outer ones, and subsequent amplification to overcome insertion and modulation losses of the transmitter. The associated amplified spontaneous emission (ASE) noise limits the performance of the entire super-channel and is hence a crucial parameter when designing comb-based transmission
systems. In the following experiments, we seek to maximize super-channel performance for a given transmission system, and to investigate the trade-off between spectral efficiency and transmission reach for the case of the GSCS.

The experimental setup to emulate a super-channel transmitter (Tx) and receiver (Rx) is depicted in Fig. 2. We use a programmable filter (Finisar WaveShaper) to equalize the power in the comb lines and to reject outer comb lines that feature too little power for sufficient modulation. The comb lines are then dis-interleaved into two sets of sub-carriers (odd and even). For the 20 GHz and 18.5 GHz line spacing, the dis-interleaving can be directly performed by the programmable filter, while for the 12.5 GHz comb, a commercially available interleaver (Optoplex Corp.) is used. The two sets of sub-carriers are amplified by two nominally identical EDFA operated in constant output power mode set to 16 dBm. Note that the equalization of the comb results in a reduction of the input power to these amplifiers. This limits the flattening of the comb lines as stronger equalization requires higher amplification afterwards, and hence more ASE noise adds to the comb lines. While this has a negative effect on the OCNR of the carriers, it helps to ensure comparable input power levels for the transmission EDFA and at the receiver input, so that the various transmission experiments can be compared. The two sub-carrier sets are then independently modulated using an IQ modulator driven by band-limited Nyquist pulses that are generated by a proprietary multi-format transmitter (Nyquist-Tx) [8,9]. Polarization division multiplexing (PDM) is emulated by splitting the combined outputs of the two Nyquist-Tx into two paths, which are recombined after different delays to form two orthogonal polarization states in a SSMF. The insets show exemplary optical spectra, RBW 0.01 nm, of the separate sub-carrier sets and the combined terabit/s data stream for the case of the 20 GHz comb and 18 GBd QPSK modulation. When using the waveshaper for dis-interleaving and flattening, we find that the crosstalk, i.e., the ratio of the power of a comb line at its allocated waveshaper output port and the residual power of the same comb line at the other output port is actually a function of the attenuation supplied to this particular comb line. We find crosstalk attenuation levels of (19.9±4.4) dB for the QPSK and (29.1±6.4) dB for the 16QAM experiments. We do not observe a correlation between crosstalk attenuation and the performance of the sub-channels, and hence conclude that our results are not limited by crosstalk effects. This finding is in accordance to the one reported in [10], where a SNR penalty of less than 1 dB is predicted for these levels of crosstalk.
Fig. 2. Schematic of the GSCS terabit/s super-channel transmitter and coherent receiver. The frequency comb is equalized and de-multiplexed into odd and even comb lines. The two sets of carriers are amplified, modulated with independent, sinc-shaped Nyquist signals and then combined in a polarization division multiplexing (PDM) scheme. Insets show the optical spectra measured using a 0.01 nm resolution bandwidth. The super-channel is either sent directly to the receiver or transmitted through up to four spans of 75 km standard single mode fiber (SSMF) with an EDFA before each span. At the receiver, the desired sub-channel is selected by a band-pass filter (BPF), amplified and coherently detected using a narrow-linewidth laser as a local oscillator (LO). The signal is recorded and analyzed using an optical modulation analyzer (Agilent N4391A). The presented constellation diagrams are obtained using an ECL as a carrier, and serve as reference measurements. The phase error that can be particularly seen in the 12 Gbd constellation diagrams as well as the stronger noise cloud for the 18 Gbd measurements is attributed to our transmitter hardware.

The super-channels were either sent directly to the Rx for back-to-back (B2B) characterization, or transmitted over up to four spans of 75 km SSMF with an erbium-doped fiber amplifier (EDFA) before each span. The launch power into the transmission fibers has been set to approximately –3dBm per sub-channel, providing a good compromise between nonlinear signal impairments and noise. As a local oscillator (LO) we use an external cavity laser (ECL) specified with a linewidth less than 100 kHz. The signals were analyzed using an optical modulation analyzer (Agilent N4391A) and with offline processing. We perform digital brick-wall filtering, polarization demultiplexing, dispersion compensation, and adaptive equalization before evaluating the bit-error-ratio (BER) and the error vector magnitude (EVM) of each sub-channel individually. The EVM subscript “m” indicates the normalization of the EVM to the maximum power of the longest ideal constellation vector.

As a performance measure of the system we test both modulation paths individually with a narrow-linewidth ECL that is comparable to the ECL used as local oscillator. With 18 Gbd modulation we achieve an average EVM\textsubscript{m} of 10.5 % and 9.8 % for QPSK and 16QAM, respectively, while an average EVM\textsubscript{m} of 8.5 % and 7.5 % is obtained for 12 Gbd modulation, respectively. The dependence of the performance on symbol rate is attributed to the limited bandwidth of our anti-aliasing filters after digital-to-analog conversion.

Assuming that the signal is impaired by additive white Gaussian noise only, a direct relation from the EVM\textsubscript{m} to the BER can be established [11]. In our experiments this assumption is not perfectly fulfilled as the constellations show a small signature of phase noise. As we see this behavior also for the reference measurements with an ECL, see insets in Fig. 2, we attribute this to our transmitter hardware rather than to the linewidth of the optical source. Nevertheless we present our results using the EVM\textsubscript{m} metric, since for the QPSK experiments we generally did not measure a high-enough number of errors within the length of one recording. For the 16QAM experiments we give both the EVM\textsubscript{m} and the BER. One can see that the EVM\textsubscript{m} slightly overestimates the signal quality, which we attribute to the small phase error introduced by our transmitter hardware as well as the fact that our EVM\textsubscript{m} measurement is non-data-aided while the relation in [11] assumes a data-aided measurement of the EVM\textsubscript{m}.
Another interesting metric would be the sub-channel OSNR. However, such an evaluation is not easily possible in our de-multiplexer setup: Due to narrowband filtering of the individual comb lines using a passband width of the order of 10 GHz, the filtered ASE background is strongly nonuniform, and we can hence not any more estimate the noise power density at the carrier wavelength from a measurement taken in the center between two carriers. We may, however, estimate the sub-channel OSNR from the OCNR measured at the output of the GSCS. For the 20 GHz comb, the OCNR is relatively uniform and amounts to approximately 127 dB Hz, which would translate into an OSNR of roughly 26 dB after modulation and back-to-back reception. In the case of the 16QAM experiments, we perform a reference experiment using a single-line ECL with an output power comparable to the total power of the flattened and de-multiplexed combs lines. We measure an OSNR at the input of our Rx of 40.5 dB in a reference bandwidth of 0.1 nm, only limited by the ASE noise of the transmission system. We hence conclude that the transmission performance of our 16QAM experiments is limited by the noise characteristics of the GSCS rather than by the ASE of the transmission system.

3.3 Experimental results

3.3.1 Experimental parameters and comparison of super-channels

We investigate six different super-channel architectures that are based on three different line spacings, 20 GHz, 18.5 GHz and 12.5 GHz, and two different modulation formats, QPSK and 16QAM. The results of all six experiments are summarized in Table 1. For each super-channel we take as many comb lines as possible, each carrying a Nyquist-WDM sub-channel. Comb lines that were too weak for the respective modulation format were suppressed by the equalization filter (equalizer “Eq.” in Fig. 2) prior to recording the data presented here. For the super-channels that were derived from the 20 GHz and the 18.5 GHz comb we use a symbol rate of 18 Gbd and hence obtain a sub-channel line rate of 72 Gbit/s for PDM-QPSK modulation and 144 Gbit/s for PDM-16QAM. A symbol rate of 12 Gbd was used for the super-channels based on the 12.5 GHz comb leading to a sub-channel line rate of 48 Gbit/s and 96 Gbit/s for the two modulation formats employed. For all symbol rates, the clock rate of the digital-to-analog converters (DAC) of the Nyquist-Tx was kept constant at 24 GHz, while the oversampling factor \( q \) for generating the sinc-shaped output pulses was adapted to \( q = 4/3 \) for 18 Gbd and \( q = 2 \) for 12 Gbd.

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<td>160</td>
<td>1.047</td>
<td>6.5 (150 km)</td>
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<tr>
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<td>15</td>
<td>72</td>
<td>1.080</td>
<td>277.5</td>
<td>1.009</td>
<td>3.6 (300 km)</td>
</tr>
<tr>
<td></td>
<td>PDM-16QAM</td>
<td>9</td>
<td>144</td>
<td>1.296</td>
<td>166.5</td>
<td>1.109</td>
<td>6.7 (150 km)</td>
</tr>
<tr>
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<td>24</td>
<td>48</td>
<td>1.152</td>
<td>300</td>
<td>1.077</td>
<td>3.6 (300 km)</td>
</tr>
<tr>
<td></td>
<td>PDM-16QAM</td>
<td>4/20</td>
<td>48 / 96</td>
<td>2.112</td>
<td>300</td>
<td>1.867</td>
<td>6.2 (300 km)</td>
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Table 1: Summary of all super-channels.

In Table 1, the aggregate line rate is obtained by multiplication of the number of sub-channels with the sub-channel line rate, and the bandwidth of the super-channel is given by the product of sub-channel number with the comb line spacing. For calculating the net aggregate data rate one needs to take into account the overhead for forward error correction (FEC). FEC schemes with 7 % overhead can cope with BER of up to \( 4.5 \times 10^{-3} \) [12], a requirement which was fulfilled for all B2B experiments.

For some transmission experiments, this BER threshold is exceeded as discussed in the subsequent sections. In these cases, some of the sub-channels require more advanced FEC codes with a larger overhead of, e.g. 20 %, having a higher BER limit of, e.g., \( 1.5 \times 10^{-2} \) [13]. We calculate the net
aggregate data rate for each super-channel after the longest tested transmission distance by taking into account the respective overhead for each sub-channel individually. The net SE is then calculated from the ratio of the net aggregate data rate and the occupied bandwidth. In the parenthesis we indicate the actual fiber transmission distance over which this spectral efficiency has been achieved.

3.3.2 Terabit/s super-channels with an 18.5 GHz comb

For the highest spectral efficiency we operate the Nyquist-Tx at a symbol rate of 18 Gbd and choose a comb line spacing of 18.5 GHz, see spectrum of Fig. 1(c). We select a total of 15 lines using the equalization filter and flatten the spectrum to the level of the weakest carrier. Fig. 3(a) shows the spectrum of the super-channel using PDM-QPSK modulation with a total aggregate line rate of 1.08 Tbit/s, measured in a resolution bandwidth of 0.01 nm. For each sub-channel the measured EVM\(m\), averaged over both polarizations, is presented in Fig. 3(b) for the B2B case and for transmission distances of 75 km, 150 km, 225 km, and 300 km. The transmission lengths are distinguished by different symbols, colors, and by an offset in the horizontal direction. Note that we could not find enough errors in the recorded number of 4,500,000 bits for evaluating the BER reliably. Therefore we conclude that the BER of all sub-channels are clearly below the threshold for second-generation forward-error correction (FEC) with 7% overhead, given by a BER of \(4.5 \times 10^{-3}\), which corresponds to an EVM\(m\) of 38.3% [11]. We hence obtain a net super-channel capacity of 1.009 Tbit/s in a bandwidth of 278 GHz, corresponding to a net spectral efficiency of 3.6 bit/s/Hz. Selected constellations diagrams of the B2B-experiments are displayed in Fig. 3(c). We compare two sub-channels, one at the border and one at the center of the super-channel spectrum. They perform similar for both polarizations.

The bandwidth requirement can be reduced by a factor of two when upgrading the system from QPSK to 16QAM signaling. This doubles the line rate per channel but requires a higher optical signal-to-noise-ratio (OSNR). To this end we increase the equalization power level for flattening the comb, i.e., the average attenuation is decreased, which leads to carriers with a higher power. However, only fewer comb lines contribute the required power, hence the number of sub-channels is reduced from 15 to 9. Because a higher power level is input to the EDFA, the amplification and the ASE contribution is lower, leading to a larger OCNR. Additionally, the smaller attenuation results in a reduced crosstalk of the waveshaper, see Section 3, third paragraph. Spectrum, EVM\(m\) and measured BER are presented in Figs. 3(d)–3(f). For short transmission distances (B2B), the BER stays below the standard FEC limit for 7% overhead. For a transmission distance of 150 km, seven of the nine sub-channels exceed the BER mark for standard FEC, and implementations with larger overhead, i.e., 20% overhead, become necessary. The remaining two sub-channels fall below the FEC threshold with 7% overhead even after transmission over 150 km. The aggregate line rate (net data rate) of this super-channel amounts to 1.296 Tbit/s (1.109 Tbit/s), corresponding to a (net) spectral efficiency of 7.8 bit/s/Hz (6.7 bit/s/Hz). This is among the highest values achieved for 16QAM in terabit/s super-channels.
Fig. 3. Spectra, signal quality and constellations for super-channel transmission with an 18.5 GHz comb. Left column for QPSK, right column for 16QAM. (a) Spectrum of the super-channel derived from a 18.5 GHz comb with 18 GBd PDM-QPSK modulation (RBW 0.01 nm). The sub-channel number increases with carrier frequency. (b) Measured EVM\textsubscript{m} for each sub-channel and transmission over different distances. We find that all 15 sub-channels perform better than the threshold for second-generation FEC with 7\% overhead, yielding a total data rate of 1.009 Tbit/s transmitted over 300 km. (c) Measured constellation diagrams for sub-channels 1 and 8 of the PDM-QPSK experiment. (d) Spectrum of the super-channel derived from a 18.5 GHz comb with 18 GBd PDM-16QAM (RBW 0.01 nm). (e-f) Measured EVM\textsubscript{m} and BER for each sub-channel and transmission over different distances. We find that 2 (7) sub-channels perform better than the FEC threshold with 7\% (20\%) overhead, yielding an aggregate net data rate of 1.109 Tbit/s transmitted over 150 km. (g) Measured constellation diagrams for sub-channel 8 of the PDM-16QAM experiment.

In Fig. 3(g) we show the constellation diagram of the central sub-channel 8 in two polarizations. Note that the smaller noise clouds as compared to Fig. 3(c) (QPSK) for the same sub-channel is a direct consequence of the higher power level of the flattened comb lines in the 16QAM case, which yields a higher OSNR of all sub-channels.

### 3.3.3 Terabit/s super-channels with a 20 GHz comb

A more robust super-channel can be generated by increasing the guard band. To this end, we increase the line spacing of the comb to 20 GHz, see spectrum in Fig. 1(b), while keeping the same symbol rate at the Nyquist-Tx. We select again 15 comb lines, 13 of which we flatten to the same power level as in the 18.5 GHz experiment for better comparison. The outermost carriers do not
reach this power level and hence their performance drops below that of the inner 13 carriers. This can be seen in the spectrum as well as in the EVM\textsubscript{m} results for QPSK modulation, Figs. 4(a) and 4(b). Taking into account the inner 13 sub-channels, the super-channel aggregate line rate (net data rate) amounts to 0.936 Tbit/s (0.875 Tbit/s), with a (net) spectral efficiency of 3.6 bit/s/Hz (3.4 bit/s/Hz).

Selected constellations diagrams of the B2B-experiments are displayed in Fig. 4(c). We compare two sub-channels, one at the border of the comb (sub-channel 1, also representative for sub-channel 15), and the central sub-channel 8 (representative for sub-channels 2 to 14). Sub-channels 1 and 15 suffer from low carrier power and therefore from a small OSNR. However, the central sub-channels 2 to 14 have an EVM\textsubscript{m} which is slightly better than that of the corresponding sub-channels of the 18.5 GHz experiment. We attribute this to the larger guard band that reduces inter-channel interference originating from imperfect Nyquist pulse shaping.

This fact becomes even more evident when comparing the 16QAM 20 GHz comb experiment Figs. 4(d)–4(f) with the 18.5 GHz comb experiment in Figs. 3(d)–3(f). We achieve 6 (2) sub-channels that are better than the 7 % (20 %) FEC limit after 150 km of fiber transmission. The aggregate line rate (net data rate) amounts to 1.152 Tbit/s (1.047 Tbit/s). The (net) spectral efficiency amounts to 7.2 bit/s/Hz (6.5 bit/s/Hz). These results must be compared to the case of the 18.5 GHz comb and illustrate the trade-off between super-channel capacity and reach: For a comparable capacity, we used 9 sub-channels, but only 2 (7) were better than the 7 % (20 %) FEC limit after transmission over 150 km. We conclude that transmission with the 20 GHz comb has the larger capacity for a reach, where the channels with a FEC overhead of 20 % would drop out.

In Fig. 4(g) we show the constellation diagram of the central sub-channel 8 in two polarizations. The smaller noise clouds as compared to Fig. 4(c) (QPSK) for the same sub-channel follow from the higher power level of the flattened comb, see Figs. 3(c) and 3(g).
Fig. 4. Spectra, signal quality and constellations for super-channel transmission with a 20 GHz comb. Left column for QPSK, right column for 16QAM. (a) Spectrum of the super-channel derived from a 20 GHz comb with 18 Gbd PDM-QPSK modulation (RBW 0.01 nm). The sub-channel number increases with carrier frequency. (b) Measured EVM for each sub-channel and transmission over different distances. We find that 13 sub-channels perform better than the threshold for second-generation FEC with 7% overhead, yielding a total data rate of 0.875 Tbit/s transmitted over 300 km. (c) Measured constellation diagrams for sub-channels 1 and 8 of the PDM-QPSK experiment. (d) Spectrum of the super-channel derived from a 18.5 GHz comb with 18 Gbd PDM-16QAM (RBW 0.01 nm). (e-f) Measured EVM and BER for each sub-channel and transmission over different distances. We find that 6 (2) sub-channels perform better than the FEC threshold with 7% (20%) overhead, yielding a total data rate of 1.047 Tbit/s transmitted over 150 km. (g) Measured constellation diagrams for sub-channel 8 of the PDM-16QAM experiment.

3.3.4 Terabit/s super-channels with a 12.5 GHz comb

In a last set of experiments, we take advantage of the tunability of the GSCS by adapting the line spacing and center frequency to the 12.5 GHz ITU-grid, see spectrum in Fig. 1(d). This enables the use of a commercial fixed interleaver to separate odd and even sub-carriers. The interleaver exhibits an excellent extinction of the odd carriers in the path of the even carriers, and vice versa. The programmable filter is then used for equalization only.
Coherent UBL measured Rev2.0
KIT, DCU, III-V Lab, CNRS (ID 619591)

BIG PIPES Broadband Integrated and Green Photonic Interconnects

Fig. 5. Spectra, signal quality and constellations for super-channel transmission with a 12.5 GHz comb. Left column for QPSK, right column for mixed QPSK / 16QAM. (a) Spectrum of the super-channel derived from a 12.5 GHz comb with 12 GBd PDM-QPSK modulation (RBW 0.01 nm). The sub-channel number increases with carrier frequency. (b) Measured EVMₘ for each sub-channel and transmission over different distances. We find that all 24 sub-channels perform better than the threshold for second-generation FEC, yielding a total data rate of 1.077 Tbit/s transmitted over 300 km. (c) Constellation diagrams for the sub-channels 1 and 2. (d) Spectrum of the super-channel derived from a 12.5 GHz comb with 12 GBd PDM-16QAM (RBW 0.01 nm). (e-f) Measured EVMₘ and BER for 12 GBd PDM-16QAM on the inner comb lines (white background) and PDM-QPSK on the outer lines (green background), again for different propagation distances. We find that 14 (10) sub-channels (10 (10) channels using PDM-16QAM and 4 channels using PDM-QPSK) perform better than the threshold for FEC with 7% (20%) overhead, yielding a total data rate of 1.867 Tbit/s, transmitted over 300 km. (g) Measured constellation diagrams for sub-channel 12 of the PDM-QPSK / PDM-16QAM experiment.

For the QPSK experiments, we use again the same equalization level as for the 18.5 GHz and the 20 GHz comb while reducing the symbol rate to 12 GBd. This leads to 24 sub-channels with EVMₘ values well below the 7% FEC limit, see Fig. 5(a) for the super-channel spectrum and Fig. 5(b) for the EVMₘ results. The four outermost channels do not reach the power level which was used for flattening, and hence drop in performance. The (net) capacity of this super-channel is 1.152 Tbit/s (1.077 Tbit/s), and the (net) spectral efficiency amounts to 3.8 bit/s/Hz (3.6 bit/s/Hz). Fig. 5(c) shows selected constellation diagrams for the QPSK experiment in the B2B case. The constellation diagrams represent peripheral (example: sub-channel 1) and central sub-channels (example: sub-channel 12).
sub-channel 12), respectively.

We finally boost the super-channel aggregate line rate to 2.112 Tbit/s by increasing the equalization level and by admitting the weak outer comb lines, too. This enables 16QAM modulation on 20 sub-channels in the center, while 4 of the outer sub-channels still enable QPSK operation below the 7% FEC threshold, see Figs. 5(d)–5(f). The aggregate net data rate amounts to 1.867 Tbit/s with a net spectral efficiency of 6.2 bit/s/Hz for transmission over 300 km. Fig. 5(g) shows the PDM-16QAM constellation diagram of a central 16QAM sub-channel.

Comparing the performance of the individual sub-channels for both super-channels with the 12.5 GHz GSCS it is possible to observe a slight reduction of the EVMₘ and the BER with increasing sub-channel number. This performance dependence on the sub-channel number seems to be correlated with the variations of the OCN₀R of the comb lines as shown in Fig. 1(d). Note that, also the 18.5 GHz GSCS exhibits strong variations of the OCN₀R, but they do not seem to be correlated with the respective EVMₘ. We believe that in contrast to operation at a symbol rate of 12 Gbd, the cut-off frequency of the anti-aliasing filters becomes effective at the present symbol rate of 18 Gbd (as explained in Section 3 Paragraph 5), and this dominates the OCN₀R-related performance degradation.

4 Coherent UBL using a 42 GHz QD-MLLD and FFH phase noise reduction

4.1 Comb source and phase noise reduction

The QD-MLLD used in this work has a free spectral range of 42 GHz. The active region consists of 6 layers of InAs quantum dashes emitting at 1.55 µm, separated by InGaAsP barriers in a dash-in-a-barrier design [14]. A buried ridge waveguide of 1.25 µm width confines the optical mode. Feedback is provided by the cleaved end facets of the QD-MLLD. The total length of the device is 980 µm. We operate the QD-MLLD at a constant current of 338 mA, which is optimized for a narrow RF beatnote featuring 16 kHz full width at half maximum (FWHM) along with minimal side peaks. The combination of large optical linewidth and a narrowband RF beatnote indicates a high correlation of the comb line’s phases [15]. The output spectrum is depicted in Fig. 6(a).

The FFH phase noise reduction scheme is illustrated in Fig. 6(b). A small percentage of the power of the comb is tapped, a single line is filtered out, amplified and mixed with a narrow-linewidth local oscillator (LO) laser (Koheras AdjustiK) that is tuned to an offset of 8 GHz from the comb line. The beat signal at 8 GHz, created by detection with a balanced photodetector, is filtered, amplified and fed to a Mach-Zehnder modulator (MZM) that is biased at zero transmission and driven by a sinusoidal. The MZM generates two side modes at ±8 GHz while suppressing the original comb line. It was shown in [16] that the upper side mode (green lines in Fig. 6(c) and (d)) exhibits reduced phase noise. Other offset frequencies could also be chosen – for our setup, 8 GHz represents the best tradeoff between a high offset to allow separating the two sidebands and a low offset to not run into bandwidth limitations of the equipment.
Fig. 6 Setup for feed-forward heterodyne (FFH) phase noise reduction. (a) Optical spectrum of the 42 GHz comb featuring a 3 dB bandwidth close to 1.4 THz and an average output power of 10 dBm. (b) Experimental setup. Light from the QD-MLLD is collected using an anti-reflection coated lensed fiber followed by an isolator to avoid back-reflection into the laser cavity. For the FFH scheme, a small portion of the comb is tapped and a single line is filtered from the comb spectrum. This line is mixed with a narrow-linewidth LO laser that is offset by 8 GHz. The resulting RF beat generated in a balanced photodetector is filtered, amplified and fed to a MZM that is biased at minimum transmission for carrier-suppressed modulation. This modulation generates two sidebands around each comb line, cf. (c). The upper side mode (green line) exhibits reduced phase noise while the lower side mode (red line) features enhanced phase noise. (d) Optical spectrum of the output from the FFH scheme showing pairs of lines surrounding the suppressed comb line. The two smaller peaks within the free spectral range correspond to spurious harmonics generated by the carrier-suppressed modulation. (e) Result of the heterodyne optical linewidth measurement for the original comb lines (orange) and the lines with reduced phase noise at the output of the FFH scheme (green). It can be clearly seen that the linewidth of all modes is reduced. Line # 0 corresponds to the comb line that is mixed with the offset LO and is used to generate the MZM drive signal.

We confirm the optical linewidth reduction through a direct measurement, see Fig. 6(e). To this end we beat each line with a narrow-linewidth laser and evaluate the width of the beat measured with a fast photodiode and a radio frequency (RF) spectrum analyzer [17]. The FFH scheme reduces the optical linewidth for all 30 modes that have been tested. For the center modes, the resulting linewidth is below 1 MHz, which is sufficiently low for application in coherent data transmission with current digital signal processing (DSP). Typical linewidth requirements for an 18 GBd QPSK signal are 3.8 MHz [18] or 7.4 MHz [19], depending on the receiver implementation.

4.2 Coherent terabit data transmission employing FFH phase-noise reduction

After FFH phase noise reduction, the frequency comb exhibits pairs of lines that correspond to the upper and lower modulation sidemode, Fig. 6(c). For data transmission we want to use the upper sidemodes (green lines) which feature the reduced phase noise. Fig. 7(a) shows a schematic of the WDM data transmission test used in this work. The upper side modes are filtered and dis-interleaved into odd and even carriers using a Finisar waveshaper (WS) while the lower side modes are suppressed. After dis-interleaving, we modulate even and odd carriers with 18 GBd sinc-shaped QPSK signals using a pseudo-random bit sequence of length $2^{11}-1$. The signals are combined and either tested in (A) a back-to-back (b2b) configuration, or (B) amplified and sent through a 75 km spool of standard single mode fiber (SSMF). The receiver comprises filters, a pre-amplifier and an optical modulation analyzer (OMA, Keysight N4391A) that uses coherent detection with an external cavity laser (ECL) as LO. We evaluate the signal quality using the Keysight VSA software. Signal processing includes digital brick-wall filtering, dispersion compensation, and adaptive equalization.
before evaluating the bit-error-ratio (BER). Fig. 7(b) shows constellation diagrams with and without using the FFH scheme for the case of line # 0. The reduction of the phase error can clearly be seen.

Fig. 7 Setup for WDM data transmission and measured results. (a) Upper sidemodes of the output from the FFH scheme are selected and split into odd and even carriers for independent modulation with QPSK signals at a symbol rate of 18 Gbd. The signals are combined using a 3 dB coupler and tested either in a back-to-back (btb) configuration or amplified and transmitted over 75 km of standard single-mode fiber (SSMF). The receiver comprises filters, a pre-amplifier and an optical modulation analyzer (OMA) that uses a coherent detection scheme with an ECL as local oscillator (LO). (b) Constellation diagrams obtained with and without the FFH-scheme. (c) Spectra of odd (top) and even (bottom) comb lines after dis-interleaving. (d) Optical spectrum of the 30 data channels. (e) Bit error ratio results for 30 channels when applying the FFH-scheme. An aggregate data rate of 0.971 Tbit/s could be recovered within the limits of forward-error correction with 7 % overhead.

Fig. 7(c) shows the dis-interleaved comb spectra. The extinction ratio of the lower, unwanted side mode is better than 26.5 dB with an average of 33.8 dB. This was achieved by narrowing the bandwidth of the programmed filters, which unfortunately also leads to an additional attenuation for some of the carriers due to the inherent interpolation of the filter shape in the WS, where each pixel covers a frequency range of about 5 GHz. Note that this only represents a limitation of our measurement setup and could be solved when using, e.g., a periodic filter with narrow pass-bands such as a high-finesse Fabry-Perot etalon. A second possibility to increase the extinction ratio would be to replace the MZM in the FFH scheme with an IQ modulator driven as a frequency shifter, thereby only generating a single side mode. The spectrum of the modulated comb is depicted in Fig. 7(d) for the btb case. It comprises 30 channels, which corresponds to a line rate of 1.08 Tbit/s. The average OSNR of the channels at the Rx (input to the 0.6nm filter) is 26.4 dB for the btb case and 25.0 dB after 75 km fiber transmission. BER results for btb and 75km are depicted in Fig. 7(e). For btb, all 30 channels are below the BER threshold of $4.5 \times 10^{-3}$ for a standard forward-error correction (FEC) scheme with 7 % overhead, corresponding to a net data rate of 1 Tbit/s. After transmission, the channel with index −14 exceeds the FEC limit, resulting in only 29 channels within the 7 % FEC limit. This corresponds to a net data rate of 0.971 Tbit/s after transmission. The data rate could be doubled with polarization multiplexing, which could not be tested in these experiments due to limited availability of hardware. Nevertheless, our results demonstrate that FFH phase-noise reduction can be used to simultaneously reduce the optical linewidth of a multitude of optical lines that are derived from one semiconductor QD-MLLD, thereby enabling the first coherent data transmission experiment using a frequency comb from a QD-MLLD.
5 References


