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Self-homodyne 24×32-QAM superchannel receiver enabled by all-optical comb regeneration using brillouin amplification

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Abstract: We demonstrate and characterize an all-optical self-homodyne (SH) frequency superchannel enabled by comb regeneration at the receiver. In order to generate the superchannel, we use a frequency comb with 26 carriers spaced by 25 GHz at the transmitter, from which 24 carriers are modulated with polarization-multiplexed 32 quadrature amplitude modulation (PM 32-QAM) data. To enable comb regeneration at the receiver side, the two central carriers remain unmodulated. High fidelity comb regeneration is achieved by filtering the two unmodulated carriers with an approximately 25 MHz wide optical filter based on Brillouin amplification before a parametric mixer. The carriers from the regenerated comb are then used as local oscillator for SH detection. We demonstrate that all 24 carriers can be detected with an optical signal-to-noise ratio (OSNR) penalty lower than 2.5 dB in a back-to-back scenario. We also demonstrate that the whole superchannel can be transmitted through 120 km of single-mode fiber (SMF) and be detected with bit-error rate (BER) below 0.015.

OCIS codes: (060.1660) Coherent communications; (190.4410) Nonlinear optics, parametric processes; (060.2920) Homodyning; (290.5900) Scattering, stimulated Brillouin.

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#278253 http://dx.doi.org/10.1364/OE.24.029714
Journal © 2016 Received 7 Oct 2016; revised 15 Nov 2016; accepted 2 Dec 2016; published 14 Dec 2016

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1. Introduction

The use of higher-order quadrature-amplitude modulation (QAM) formats is steadily increasing in optical communications in order to enable system with high spectral efficiency (SE) [1–3]. However, the use of these modulation formats requires low-linewidth transmitter and receiver lasers in combination with complex digital signal processing (DSP) algorithms for frequency and phase estimation unless a self-homodyne (SH) receiver is employed. In a SH receiver, the complexity for phase estimation algorithms is relaxed at the expense of using a local oscillator (LO) with ideally the same phase information as the transmitted carrier. To obtain such kind of LO, the transmission of an unmodulated carrier multiplexed in an orthogonal polarization with a modulated signal has been proposed [4–6]. This technique however halves the SE and requires an all-optical polarization demultiplexing unless digital SH is employed [7]. In order to increase the SE of SH systems, the use of interleaved polarization multiplexing (PM) has been proposed [8], but this technique still requires the use of all-optical polarization demultiplexing. Transmission of the carrier at another frequency has also been demonstrated [9–11]. The need for sending a pilot carrier for each data signal reduces the SE as well. Moreover, this technique requires to frequency shift the unmodulated carrier at the receiver which has been demonstrated by using an optical phase-locked loop (OPLL) [9], using optical injection locking (OIL) and a intensity modulator [10], or four-wave mixing (FWM) [11]. In all these cases, the complexity of the necessary synchronization between the transmitter and receiver clocks should also be taken into account. Using orthogonal frequency-division multiplexing (OFDM), the use of SH detection has also been studied [12, 13]. Recently it was demonstrated the use of OIL for SH detection with an spectral overhead from 5% to 8% [14]. A spectrally efficient SH receiver has been demonstrated using a 19-core fiber in which a dedicated core was used to transmit the pilot tones [15].

Suggested in [16], comb regeneration has gained attention recently to improved the SE of SH detection without any requirement on the modulation format in standard single-mode fibers (SMFs) [17, 18]. This technique requires the use of a comb at the transmitter which is regenerated at receiver end. In order to regenerate the comb with high fidelity, the carrier spacing and the phase of one of the carriers needs to be known at the receiver end. These two parameters can be easily obtained all-optically by transmitting two unmodulated carriers. Comb regeneration has been demonstrated by using OIL on these two carriers and a parametric comb [18]. Linewidth measurements of the regenerated carriers showed promising results but data transmission is required for a complete concept evaluation. Data transmission is sensitive to a broader range of system impairments such as high-frequency noise which can degrade performance. Narrow filtering of the unmodulated lines at the receiver side is therefore required to avoid such penalty.

In this work, for the first time SH frequency superchannel transmission using all-optical comb regeneration is demonstrated. The all-optical comb regeneration is achieved by using Brillouin amplifiers for the filtering of the unmodulated carriers before the parametric mixer. A frequency superchannel consisting on 24 carriers modulated with 20 GBaud PM 32-QAM and 25 GHz channel spacing are SH detected using the regenerated comb as LOs. The penalty caused by the comb regeneration compared with an ideal comb is analyzed in a back-to-back (B2B) scenario. We demonstrate that all 24 carriers can be SH detected with a penalty lower than 2.5 dB compared to the case of ideal SH receiver. Furthermore, we also investigate the performance of the proposed receiver in a single-span 120 km SMF transmission experiment. In this case, all transmitted 24 channels can also be detected with bit-error rate (BER) below 0.015.

2. Experimental setup

The experimental setup is shown in Fig. 1. A laser at 1545.1 nm with about 5 kHz linewidth fed an electro-optic (EO) comb. The EO frequency comb consisted of a Mach-Zehnder modulator (MZM) and a phase modulator in order to generate about 26 carriers with 25 GHz spacing and flat spectrum [19, 20]. After the EO-comb and an erbium-doped fiber amplifier (EDFA), we divided the 26 carriers into two arms. In one arm, we selected the two central lines (1545.1 and 1545.3 nm) by using a 0.8 nm filter followed by an EDFA and a 0.25 nm filter. In the other arm, these two carriers were removed by an optical processor (OP). An interleaver (IL) split the remaining 24 carriers into even and odd carriers which were modulated by two independent IQ modulators driven by decorralated 20 GBaud 32-QAM signals shaped as square-root raised cosine with roll-off of 5%. After each modulator, PM was emulated by splitting the signal, delaying one arm with an extra 1 m patchcord and combining with a polarization-beam combiner (PBC). Afterwards, the even and odd data channels were combined before being amplified. In the B2B analysis, the modulated signals and unmodulated carriers were not combined to be able

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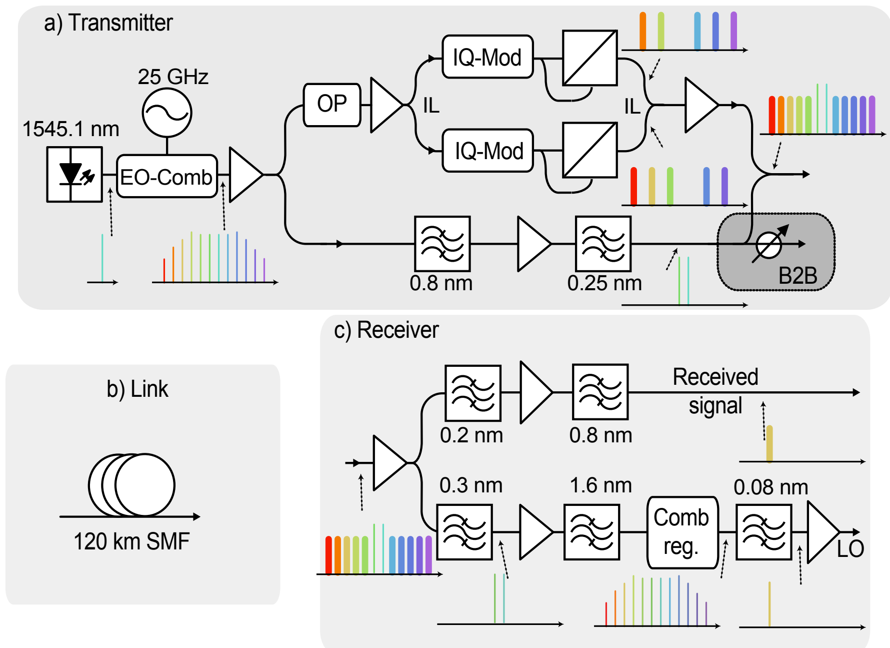

Fig. 1. Schematic of the experimental setup of the transmitter (a), transmission span (b) and receiver (c).

to study the required optical signal-to-noise ratio (OSNR) in the modulated signal for different OSNRs of the unmodulated carrier. When performing transmission through 120 km of SMF (loss of 25 dB), both modulated and unmodulated carriers were combined before the SMF. The spectrum of the transmitted superchannel can be seen in Fig. 2(a).

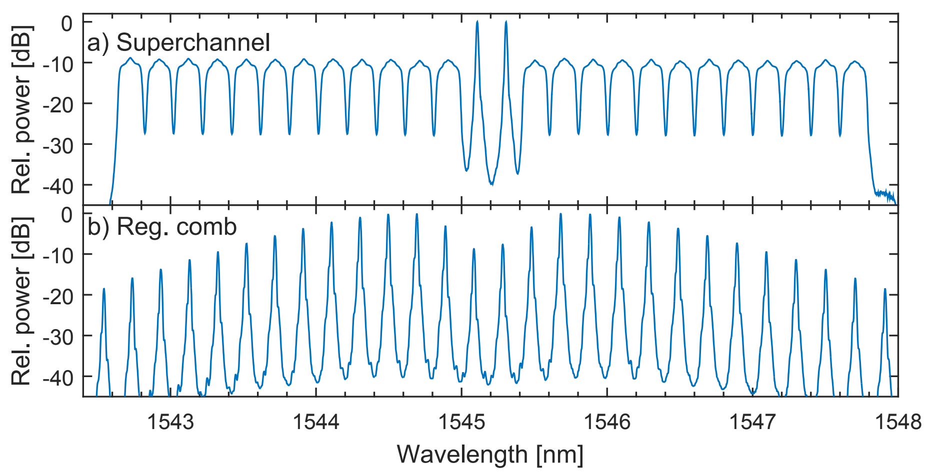

Fig. 2. a) Spectra of the transmitted superchannel. b) Spectrum of the regenerated comb. The resolution is 0.013 nm

At the receiver, Fig. 1 (c), the combined signal were divided into two arms. In one branch, the data channel was selected by using of a programmable filter with bandwidth of 0.2 nm, an EDFA and a second programmable 0.8 nm filter. In the other arm, the two unmodulated carriers

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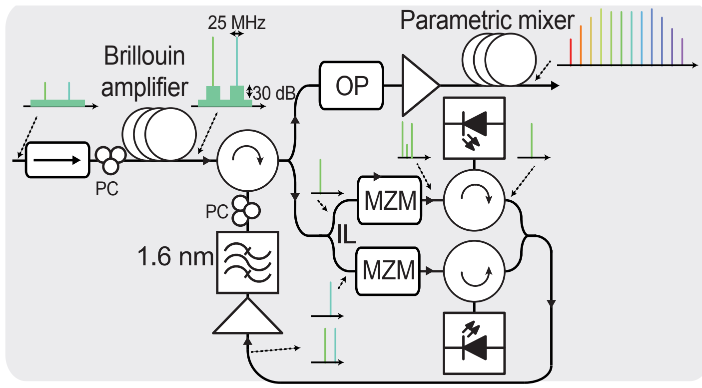

Fig. 3. Schematic of the all-optical comb regeneration stage.

went through a 0.3 nm filter followed by an EDFA and a 1.6 nm filter. In the B2B analysis, the data signals were directly sent to the upper arm and the unmodulated carrier to the lower arm since the data signals and the unmodulated carriers were not combined in the transmitter. After selecting the two unmodulated carriers, the frequency comb was regenerated and one regenerated carrier was selected to be used as LO by a programmable filter with bandwidth of about 0.08 nm. Batches of 40 μs of data were sampled at 50 Gsamples per second using a scope with bandwidth of 23 GHz. The offline DSP consisted of low-pass filtering to remove any remaining neighbour signal, compensation of quadrature imbalance, downsampling to 2 samples per symbol, dispersion compensation, and decision-directed least-mean square (DD-LMS) with 33 taps.

The comb regeneration, Fig. 3, was performed as follows. The two unmodulated carriers were sent through an about 30 m highly-nonlinear fiber (HNLF) in which they were narrowly filtered by using Brillouin amplification. The input power per carrrier into the HNLF was about -7 dBm and the polarization was manually optimized by a polarization controller (PC). The pumps used for Brillouin amplification were obtained by separating the two carriers after the Brillouin amplifier, amplitude modulating each carriers with a 9.652 GHz sinusoidal signal, and selecting each up-shifted carrier with an OIL laser (distributed feed-back laser). The injection ratio was about 40 dB in order to achieve as high as possible sideband suppression. The two OIL outputs were combined, amplified and filtered by a 1.6 nm filter before being sent into the HNLF in the counter-popragating direction with a combined power of about 32.5 dBm. The on-off gain of the Brillouin amplifier was about 30 dB and the bandwidth (measured with an electrical spectrum analyzer) was around 25 MHz, which is a typical value in silica fibers [21]. The frequency comb was regenerated by filtering the two carriers after Brillouin amplification with an OP in order to suppress any remaining modulated signal. The two carriers were then amplified and launched into a parametric mixer consisting of three HNLF broadening stages with compression stages of SMF in between each pair of HLNF, similar to previous published parametric combs [22]. The regenerated comb is shown in Fig. 2(b). The small peaks at around 0.08 nm from the carriers show that the regenerated comb still suffered from Rayleigh back-scattered from the upshifted pumps since the optical processor could not remove it due to the small separation between the unmodulated carriers and the Brillouin pumps. The design of a band-stop filter with sufficient extinction-ration in the OP was not possible since one of the Brillouin pumps is located in between both unmodulated carriers, only spaced by 9.652 GHz from one, and by 15.4 GHz from the other one. Larger suppression of Rayleigh scattering from the Brillouin pumps could be achieved by splitting the carriers after Brillouin amplification, narrow optical band-pass filtering each carrier and combining them. Despite the comb lines were not equalized in power, the

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minimum power into the EDFA boosting the LO power into the coherent receiver was about -12 dBm. Therefore, no major OSNR degradation is expected in this stage. This input power was mainly limited by the loss of the optical processor (about 8 dB).

3. Experimental results

In this section, we present the results of our experiments, including both the B2B analysis as well as the transmission through 120 km of SMF .

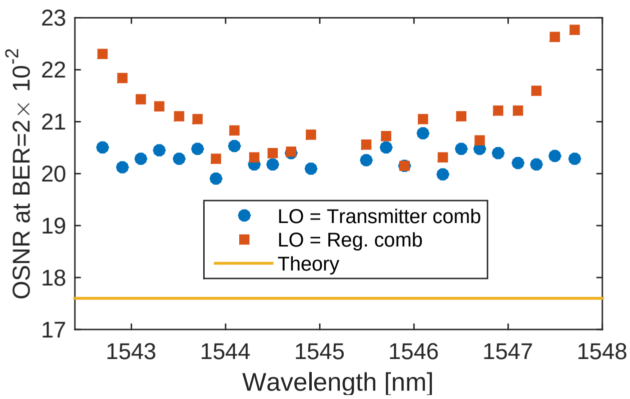

Fig. 4. Required OSNR for BER=2×10^{-2} in a B2B scenario when using the transmitted comb as LO, and when using the regenerated comb as LO with an input OSNR of 22 dB.

3.1. Back-to-back analysis

In Fig. 4 we show the required OSNR for each data channel to obtain a BER equal to 0.02 when the unmodulated carriers had an OSNR of about 22 dB. For comparison purpose, we also show the required OSNR for detecting each data channel using the transmitter comb as LO. As can be seen, the required OSNR when using the transmitter comb as LO varies from 19.8 to 20.8 dB, with an average of around 20.3 dB which is about 2.7 dB higher than the theoretical value. This penalty is mainly attributed to the transmitter and receiver implementation as well as signal OSNR degradation in the transmitter. Since the signals were noise loaded by the EDFA after the 0.2 nm filter, OSNR degradation in the transmitter was not taken into account in these measurements. When using the regenerated comb as LO, we see that for the about 12 central lines the penalty is negligible. Beyond this line, the penalty increases with separation from the central carriers. The increased penalty for the outer data channels is mainly caused by the scaling of the noise in a parametric comb. In the Appendix, we discuss the phase noise scaling using a simplistic theoretical analysis which agrees with the experimental results. The constellation for the signals at 1545.7 nm and 1547.7 nm is shown in Fig. 5. The signal OSNR was 27 dB to evaluate the effect of the LO on the received constellations. As can be seen the signal at 1547.7 nm suffer from LO noise degradation. Due to the degradation of the outer LO carriers, three data channels, 1543.3 nm, 1547.5 nm and 1547.7 nm, require an OSNR larger than 22 dB for BER=0.02. In this case, the channel that required larger OSNR, 20.8 dB, was centered at 1547.7 nm. Therefore, the largest penalty to detect the whole superchannel with BER below 0.02 is about 2.5 dB. We should clarify that the value of 22 dB OSNR for the unmodulated carriers was selected in order to minimize the OSNR penalty caused by the comb regeneration, but still lower than the highest OSNR required in one of the data channels.

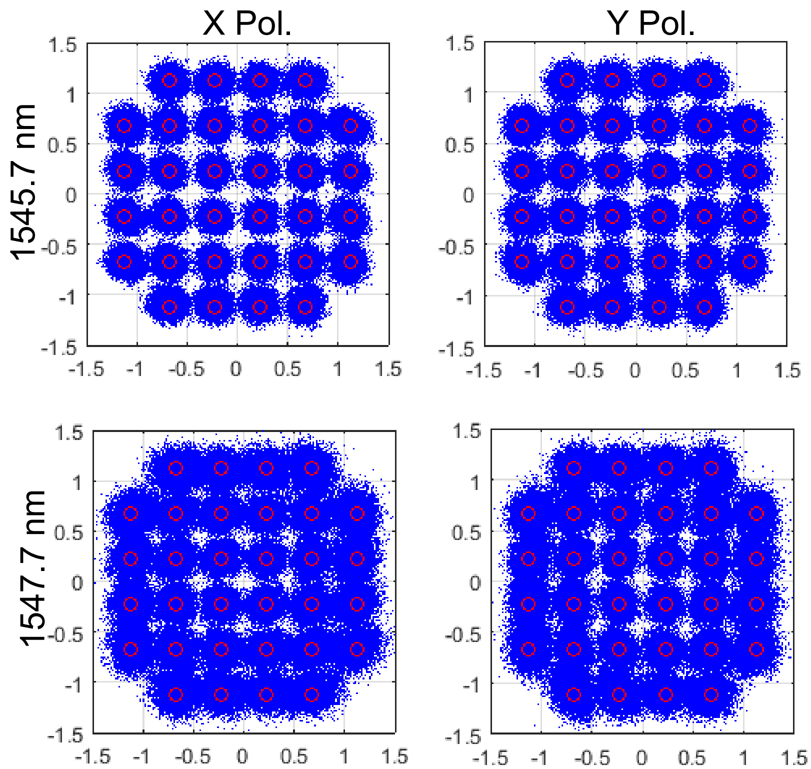

Fig. 5. Constellation diagrams for the signals at 1545.7 nm and 1547.7 nm. The signal OSNR is 27 dB and the regenerated carriers are used as LO. The input OSNR per carrier to the comb regeneration stage is 22 dB.

3.2. Transmission results

We also analyzed the BER of the proposed scheme after 120 km SMF transmission. As benchmark, we compared the BER of the received superchannel with regard to an intradyne receiver in which we used a tunable laser with linewidth of about 100 kHz as LO. In this case, we included frequency-offset estimation and a blind phase search for each symbol with 64 test angles and averaging block size of 128 symbols. The total launch power was varied from 10 to 15 dBm, with equal power for each carrier (we did not optimize the ratio between the unmodulated and modulated power). The BER for the intradyne case and the homodyne case is plotted in Fig. 6. In the case of intradyne receiver, the BER is practically the same for launch power in the range from 11 dBm to 14 dBm. We can observe that the BER for launch powers of 10 dBm and 15 dBm is slightly worse. In the case of the regenerated comb, the optimum launch power is from 10 dBm to 13 dBm. A BER increase can be seen for launch powers of 14 dBm and 15 dBm, highlighting that fiber nonlinearities can penalize the comb regeneration. The BER for all data channels is heavily degraded when the launch power is 15 dBm. When operating at the optimum launch power, the BER with the regenerated comb is degraded as the line number increases. Despite this effect, for the cases of 11 and 12 dBm launch power, the maximum BER is below 1.5×10^{-2}.

4. Discussion

Our experimental analysis is a proof of principle demonstrating that the proposed scheme is feasible for SH detection of higher-order QAM signals. We have shown that by transmitting 2

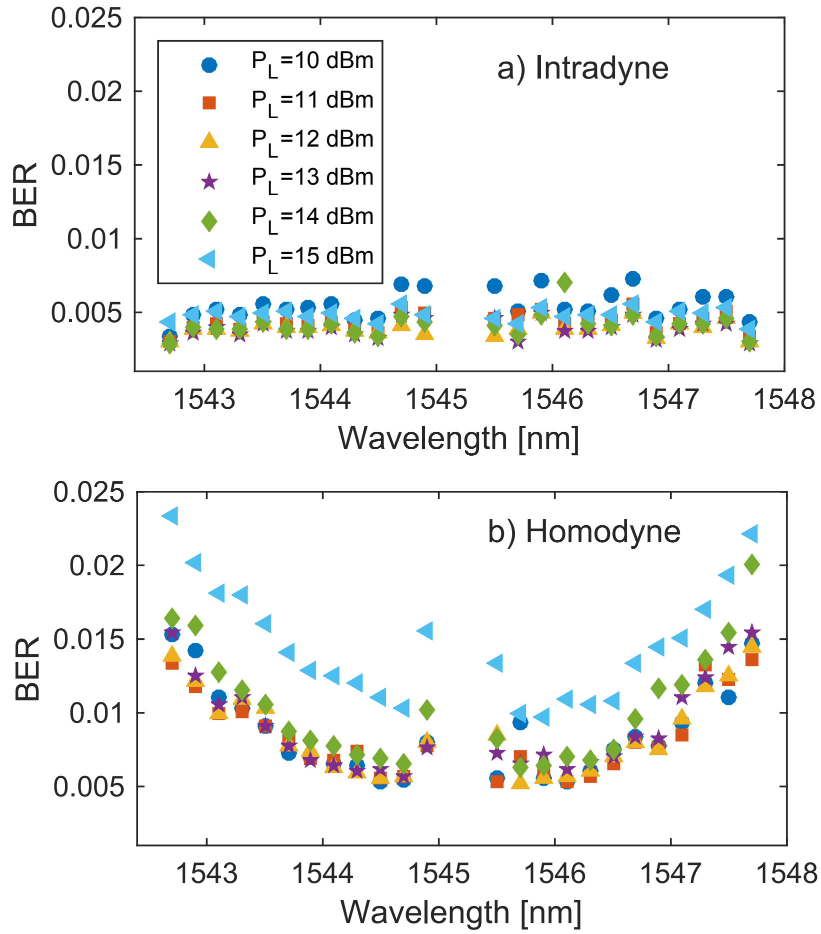

Fig. 6. BER of each data channel after 120 km SMF transmission for the cases of a) intradyne and b) SH receivers. P_L indicates the total launch power into the span.

unmodulated carries, 24 data channels can be detected in a SH receiver, giving an overhead of about 8%, which is comparable to that achieved in OFDM systes [14]. The narrow gain bandwidth of Brillouin amplifiers is a key element to achieve this. Further optimization of the Brillouin amplifier could possibly allow for more channels to be transmitted without degradation. In this case the parametric comb should be optimized as well, but we should note that a parametric comb with more than 100 lines with minimum of 40 dB OSNR per carrier has been demonstrated [23]. Another possibility with more complexity than the system demonstrated in this paper would be the use of Brillouin amplifiers for each regenerated carrier, similar to a recent experiment in which the OSNR of a parametric comb was improved by Brillouin amplification [24].

When comparing to the intradyne system after transmission, the BER performance of the SH system is degraded. The main reason is the noise scaling in the parametric comb. However, we should note that the use of SH avoids the use of frequency estimation and dedicated phase carrier algorithm. In our case, the DD-LMS algorithm was capable of tracking the low speed phase variations caused by the fact that the signal and LO were travelling through different paths. The energy saving provided in the DSP due to the lack of phase tracking and frequency offset estimation depends on the relation of the energy consumed by these algorithms compared to dispersion compensation, and decoding [25]. We should also note that the proposed scheme is mainly aimed for metro applications in which the dispersion is limited. An interesting study lying out of the scope of this paper is the analysis of the tolerance towards the linewidth of the transmitter laser. Further investigation should also be done in order to assess the capability of the proposed scheme for signals such as PM 64-QAM, PM 128-QAM, in which the performance of the carrier recovery could degrade the performance when using an intradyne receiver. These signals impose a larger constraint on the OSNR and phase noise of the LO but they also demands a higher signal OSNR, which means that the OSNR of the unmodulated carriers to regenerate the comb would be higher. The ratio between the unmodulated and modulated carriers could also be optimized in order to achieve lower penalty from the SH receiver. The degradation of the SH scheme due to nonlinearities should be further analyzed. In a preliminary analysis, using an electrical spectrum analyzer, we observed that the unmodulated lines after Brillouin amplification were affected at high launch powers. In order to make sure that stimulated Brillouin scattering in the SMF was not affecting our measurements, we lowered the powered of the unmodulated carriers by 3 dB. In this case, we also measured similar results which confirm that stimulated Brillouin scattering was not affecting the measurements but likely cross-phase modulation, cross-polarization modulation and FWM are affecting the quality of the regenerated carriers. It would be interesting to analyze whether this system can be used for analyzing the phase noise statistics in relative short links. When comparing the proposed system with conventional SH, we should note that narrow optical filtering bandwidth on the pilot tone [6] is needed to mitigate the penalty of SH detection. In a conventional SH system in which a pilot tone is sent for each WDM channel, it would be needed as many narrow optical filters as WDM channels which contrast with our proposed scheme which only needs two narrow optical filters. We should here note that the need for two narrow optical filters only is valid in the case of a superchannel in which the data carriers and pilot tones are routed to the same destination.

The narrow-band gain of Brillouin amplifiers has enabled the SH receiver. However, the Brillouin amplifiers could be replaced by any other filtering technique which enables optical filtering with similar or lower bandwidth. For example, the use of a fiber laser in combination with narrow etalon filters has been successfully demonstrated to detect 3 Gbaud 256-QAM [9]. The same technique could be used to injection lock the two unmodulated carriers in order to regenerate the comb. OPLLs could also be used to achieve high quality carriers into the parametric mixer. The integration of a wavelength-division multiplexing (WDM) transmitter along with the integration of the parametric comb could lead to a SH receiver with minimum phase-tracking. Brillouin amplifiers, which have been recently demonstrated in silicon [26], along with an integrated non-linear optic waveguides [27] could lead to a fully integrated regeneration. The use of frequency combs generated in microring resonators [28] could also be beneficial for the proposed technique. In this case, the comb should be initiated by launching the unmodulated carriers into the microring resonator. Moreover, the free-spectral range of the microring resonators should coincide with the separation between the unmodulated carriers. If the drop port of the resonator is used, then the filtering and comb regeneration could be achieved in an single integrated device.

The analysis of the polarization dependence of the comb regeneration has not been studied in this work. In our experiments, the polarization of the unmodulated carriers into the Brillouin amplifiers was optimized by using a PC. Therefore, a polarization tracker scheme must be implemented for an out-of-lab scenario. Polarization trackers for polarized light are commercially available [29]. Depending on the polarization-mode dispersion (PMD) coefficient of the fiber and the transmission distance, one or two polarization trackers should be implemented, depending on whether the two unmodulated carriers remain co-polarized through the link. In the case of large PMD, an option for polarization tracking would be splitting the two carriers into two paths with a polarization tracking in each and combining before the Brillouin amplifier. In our experiments, the unmodulated carriers remained co-polarized through the link even their state of polarization at the SMF input was not optimized and corresponding to a random state of polarization. We should note that in the case of one pilot tone per WDM channel, there would be a need for as many polarization tracking schemes as WDM channels, which again highlights the decrease in complexity when employing the proposed scheme compared to a conventional SH scheme.

The overhead for SH detection in this paper could be further reduced by combining the proposed technique with MCF. In this case, a frequency and spatial superchannel would only require the two unmodulated carriers in one of the cores. Therefore, this core would carry two unmodulated signal and several modulated signals and the remaining cores would carry only modulated signals. Such a solution can lead to a negligible spectral overhead in order to achieve a SH receiver.

5. Conclusion

In a proof of principle, we have demonstrated an all-optical SH superchannel consisting of 2 unmodulated carriers and 24 data channels spaced by 25 GHz and modulated as 20 GBaud PM 32-QAM. The SH receiver is enabled by the comb regeneration technique using Brillouin amplification for narrow filtering and a parametric mixer. Using the regenerated comb as LO, the largest penalty is lower than 2.5 dB in a B2B case. We have also shown that the superchannel can be transmitted over 120 km SMF, and detect all data channel with BER lower than 0.015 for all data channels.

Appendix: filtering bandwidth and phase noise

The phase of the n^{th} regenerated carrier is [30]

$$\phi'(n) = n\phi'(1) - (n-1)\phi'(0), \tag{1}$$

where $\phi\prime(1)$ and $\phi\prime(0)$ are the phases of the central carriers. The phase difference between the signal carrier phase, $\phi(n)$, and the LO, regenerated carrier, is

$$\Delta\phi(n) = \phi(n) - \phi'(n) = \phi(n) - n\phi'(0) + (n-1)\phi'(0)). \tag{2}$$

This phase difference is the phase measured after coherent detection without account for the data modulation. In the absence of noise and assuming time alignment, the phase difference vanishes, $\Delta\phi(n) = 0$. However, both signal and unmodulated carriers are affected by amplified-spontaneous noise (ASE) noise after transmission. The variance of the phase difference between the data carrier and the LO is

$$E[\Delta\phi(n)]^2 = E[\phi(n)]^2 + n^2 E[\phi'(1)]^2 + (n-1)^2 E[(\phi'(0)]^2. \tag{3}$$

We can observe that the phase noise of the seed carriers is approximately enhance by a factor n^2. If we assume that both signal and seed carriers are only affected by ASE noise and taking into account that the term $E[\phi(n)]^2$ and $E[\phi'(1,0)]$ are proportional to the signal and seed carriers filtering bandwidths, we can easily deduct that when the product of n^2 and the bandwidth of the seed carrier is much lower than the signal bandwidth, the contribution of the regenerated carrier to the phase noise is negligible. However, when this product is in the order of the signal bandwidth, both contributions need to be considered. This is the case of the B2B experiment, in which penalty arose beyond the 6^{th} carrier and we have a seed filter bandwidth of about 25 MHz.

Funding

This work was financially supported by the European Research Council Advanced Grant PSOPA (291618), the Swedish Research Council (VR), and K. A. Wallenberg Foundation.