Frequency microcomb distillation for optical superchannel transmission

Chawaphon Prayoonyong

Monash University

Andreas Boes

RMIT University

xingyuan xu

Monash University

Mengxi Tan

Swinburne University of Technology

Sai Chu

City University of Hong Kong

Brent Little

Xi'an University

Roberto Morandotti

INRS

Arman Mitchell

RMIT University

Bill Corcoran

Monash University

David Moss (✉ dmoss@swin.edu.au)

Swinburne University <https://orcid.org/0000-0001-5195-1744>

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Abstract

Optical frequency combs potentially can provide a compact and efficient light source for multi-Terabit-per-second optical superchannels. However, as the bandwidth of these multi-wavelength light sources is increased, it can result in low per-line power. Optical amplifiers can be used to overcome power limitations, but the accompanying spontaneous optical noise can degrade performance in optical systems. To overcome this, we demonstrate wideband noise reduction for comb lines using a high-Q microring resonator whose resonances align with the comb lines. When applying the proposed distillation to a superchannel system at 18 Gbaud, with 64-QAM sub-channels in a > 10 Tb/s optical superchannel, we find that noise-corrupted comb lines can reduce the optical signal-to-noise ratio required for the comb by ~ 9 dB when used as optical carriers at the transmitter side, and by ~ 12 dB when used as a local oscillator at the receiver side. By filtering with a MRR, we eliminate this degradation in OSNR.

Introduction

OPTICAL frequency combs are unique light sources consisting of precisely equidistant frequency lines, that have enabled many applications ranging from spectroscopy [1]–[3] to neural networks [4], [5], and coherent optical communications systems [6]. Although frequency comb sources are commercially available, these benchtop solutions may not be suitable for many practical applications because of their size, weight, power requirements and cost. These limitations can potentially be overcome by the use of miniaturized ‘microcombs’ [7]–[9] that have proven to be attractive solutions for a wide range of applications, including microwave photonics [11–32], optical communications [33]–[35] and others.

In optical communications systems, the individual optical frequency comb lines can be deployed either as carriers at the transmitter, or as a local oscillator (LO) at the receiver, to support superchannel transmission. High capacity optical superchannels have the potential to serve future data capacity requirements in existing fiber links, where a high spectral efficiency is critical to increase the capacity and optical bandwidth of systems over standard single mode fiber. In these superchannel systems, optical frequency combs offer an attractive alternative to using a large number of conventional external cavity lasers (ECLs) to support many individual sub-bands. Furthermore, optical frequency combs also offer advantages in terms of simplifying any signal processing, while at the same time reducing the system power consumption and cost. Wide bandwidth combs can be generated either in a micro-ring resonator (MRR) with a single pump laser that induces parametric gain and nonlinear frequency conversion [10], [33], [36], [37] or by using the electro-optic effect (e.g. [38]–[40]) with a high speed modulator, without the need for a resonant cavity. Since both methods convert the power of the initial laser line to the comb lines, or sidebands, the more comb lines that are generated results in a lower power per line [41]. In addition, micro-combs generally tend to have a nonuniform spectral power distribution which can be undesirable for some applications. Hence, if the comb spectrum is flattened, using a variety of including filtering with a gain-flattening filter or a waveshaper [35], the average power per line [6], [33]–[35] will be further reduced. To compensate for this, one can amplify the comb, typically with Erbium-doped fiber amplifiers (EDFAs). In this case, however, optical noise stemming from amplified spontaneous emission

(ASE) can contaminate the amplified comb lines. In optical communications systems, this broadband noise could degrade the performance of comb lines when they are used as either carriers or LOs, particularly for high modulation formats such as 64QAM where high signal-to-noise ratios are required.

There are a variety of approaches used to purify the amplified comb lines by reducing the optical noise, including techniques such as optical injection locking [42] and stimulated Brillouin scattering (SBS) [43], [44]. However, these approaches involve limitations due to size, power consumption, and/or a limited optical frequency range.

Here, we adapt an approach employed in spectroscopy and microwave photonics [45,46], to simultaneously filter a large number of amplified EO generated frequency comb lines with a high-quality (Q) factor MRR ($Q \sim 10^6$), for applications to optical communications systems. Our results show that the performance of the system based on distilled comb lines is significantly better than that based on noisy (amplified, unfiltered) lines. The MRR filter reduces the system noise, resulting in an increase in optical signal-to-noise ratio (OSNR) by ~ 9 dB and ~ 12 dB for a system using micro-comb lines as carriers or local oscillators, respectively, while only suffering a 5% reduction in information rate, using a modulation format of 64QAM. This work demonstrates that passive filtering with a high Q MRR can significantly improve the performance of systems based on low-power optical frequency combs, thus providing an attractive path towards improving the performance of power constrained combs, as is typically the case with micro-combs.

Proof Of Concept For Comb Distillation

Amplification of low power frequency combs by an EDFA can contaminate the comb lines with optical noise, degrading the performance of optical communications systems. In these systems, this noise can have a particularly degrading effect on the overall system performance where very advanced modulation formats are used. It has been shown that MRRs with moderate Q factors can provide an attractive and compact approach to filter optical frequency combs, with the drop port of a double-bus ring providing a periodic inverse-notch profile [47]. Here, we propose and demonstrate the use of a high Q factor ($Q \sim 10^6$) MRR [48], [49] with a bandwidth of < 200 MHz to act as a narrowband filter for each comb line. In order to effectively distill comb lines simultaneously, it is crucial to accurately match the line spacing of the microcomb to the FSR of the MRR, so that the comb lines are allowed to pass, while broadband noise is rejected. Fig. 1 (a)-(b) illustrates the filtering achieved by the MRR, where comb lines are shown in black with a high noise floor (red), along with the resonator response depicted by the blue curve. Also shown is the output at the drop port of the MRR with a small portion of noise inside the resonance bandwidth around the comb lines remaining after distillation.

To demonstrate distillation, we generate an EO frequency comb using a set of phase modulators cascaded with an intensity modulator [39], before transmitting it through the MRR. It is important to match the central wavelength and line spacing of the comb with a resonance peak and FSR of the MRR, respectively, in order to minimize loss for the comb lines while attenuating the noise. While this is readily

accomplished with EO combs, for micro-combs the spacing of the MRRs used for the comb and the passive filtering would need to be closely matched during fabrication, with further fine tuning being performed possibly with thermal control.

Once the EO comb was adjusted to match both the resonance peaks and FSR of the MRR, we then compare the spectrum of the comb before and after distillation. Fig. 2 shows two optical spectra measured with 12.5 GHz (0.1 nm) resolution, with an amplified (or noisy) comb depicted in blue and a distilled comb in magenta, for an overall comb bandwidth of ~ 1.3 THz. It can be seen that the noise floor for the amplified comb is at ~ -20 dBm whereas its power per-line is ~ -10 dBm on average, resulting in an OSNR of ~ 10 dB. The slight tilt in the noise floor is caused by gain tilt of the EDFAs due to their optical frequency dependence, particularly if the input optical signal power is lower than specified for the EDFA [50].

After distillation via the MRR, the out-of-band noise, as measured with a 12.5 GHz resolution, was significantly reduced compared to the comb lines, highlighting the reduction in passed noise bandwidth by the MRRs. Comparing the power of the comb lines to the noise amplitude (ie., the OSNR) at either end of the spectrum, we observed that this was improved by approximately 20 dB, which is expected based on the difference between the ring resonance linewidth of ~ 150 MHz and the optical spectrum measurement resolution of 12.5 GHz.

This indicates that broadband noise can be significantly reduced by MRR filtering. In the context of an optical communications system, this can be used to improve the quality of optical carriers amplified from low power comb sources at the transmitter and receiver.

System Configurations

To investigate the benefits of comb distillation in both the transmit and receive configurations, the experimental setup is shown in Fig. 3 (a)-(c). An EO frequency comb was generated by cascaded three phase modulators together with one intensity modulator (Fig. 3 (a)). The resulting EO comb is shown in Fig. 2. Here, the three phase modulators were used to broaden the optical spectrum while an intensity modulator was used to flatten the spectrum [39]. The modulators were driven with amplified RF signals (CTT Inc., APW/265–3335 amplifiers). In order to transmit the EO frequency comb through the MRR with minimal loss, we adjusted the EO comb line spacing to the resonant transmission peaks of the MRR. For micro-combs, this would need to be done during fabrication to match the FSRs of the two resonators.

Initially, we swept the frequency of a CW optical signal launched into the MRR in order to find a resonance peak, located at 193.089 THz. We then set the CW laser to this frequency to form the central frequency of the EO comb. Next, to align the EO comb lines to the MRR resonances, we searched for the FSR of the MRR by launching optical noise into the MRR before measuring the response with a 150 MHz-resolution optical spectrum analyser (OSA). We measured the FSR to be ~ 19.5 GHz and, by fine tuning the EO comb spacing, further resolved this to an FSR of ~ 19.45 GHz. Note that the MRR is polarization and

temperature dependent, and so a polarization controller and thermistor with a thermo-electric cooler, were used to align the EO comb polarization with the MRR and stabilize the MRR frequency response.

After matching the EO comb spacing to the FSR of the MRR, we loaded the comb with noise by attenuating the comb from -10 to -30 dBm in total power. We then amplified this with an EDFA to bring the total EO comb power to 21 dBm. To measure the OSNR of the comb after this stage, 50% of the comb power was coupled to an OSA with a 0.1 nm resolution. The remaining signal was transmitted through the MRR, with the drop port connected to a second amplifier, followed by a wavelength selective switch (WSS), so that the comb line of interest could be used by the optical communication system. The system was configured to also allow the noise-loaded EO comb to bypass the MRR to enable a performance comparison. The comb lines were then either deployed as carrier lines at the transmitter with the ECL laser used as LO lines or the reverse (Fig. 3 (b) and (c)). The carrier power before the IQ modulator was set to 11 dBm and increased to 14 dBm when used as a LO for coherent detection.

For the optical communications system, a 23-GHz bandwidth dual-polarization (DP) IQ modulator was driven with a 64-GSa/s, 25-GHz bandwidth arbitrary waveform generator (AWG) with a 2.5% RRC, 64-QAM signal at 18 Gigabaud (GBd) to emulate superchannel transmission with this 19.45 GHz spaced EO comb. The optical signal was mixed with the corresponding LO line at the 25-GHz bandwidth coherent receiver. The signal was then sampled by an 80 GSa/s oscilloscope having a 33 GHz bandwidth. Next, the digitized signal was processed with DSP algorithms consisting of IQ imbalance and frequency offset compensation and matched filtering, before performing training based frame synchronization, equalization, and finally phase compensation. Following these DSP steps, the signal quality (Q^2) which is related to error vector magnitude (EVM) as $Q^2 = 1/\text{EVM}^2$, and bit error ratio (BER) were calculated. In addition, generalized mutual information (GMI) was also calculated with the *calcGMI.m* script to convey information rates (from <https://www.fehenberger.de/#sourcecode>).

Demonstration Of Comb Distillation For Carriers

In this section, we investigate and compare performance of the EO comb lines when used as carriers for superchannel transmission, both before and after distillation with the MRR.

- *A. Results without distillation*

In order to compare the noise reduction in the carrier lines achieved via comb distillation, we first measured the performance of the comb lines without distillation. Here, the comb lines tested in the experiment are marked by the red arrow as shown in Fig. 4

Fig. 5 shows the Q^2 , BER and GMI plotted against comb line OSNR for the comb lines indicated in Fig. 4, without employing any comb distillation. In this case, the comb lines were used as optical carriers for modulation. As seen in Fig. 5 (a), the quality factor, Q^2 , increased linearly and eventually saturated around $Q^2 = \sim 20$ dB at an OSNR of > 25 dB, suggesting that the OSNRs above 25 dB were sufficient for the

optical carriers in our system. To benchmark the performance of the EO comb lines without distillation, we measured the required OSNR at $Q^2 = 19.3$ dB, corresponding to 0.6 b/symbol or a 5% reduction in GMI for dual polarization 64QAM. At this indicative limit of $Q^2 = 19.3$ dB as illustrated with a yellow dashed line, we found that the required OSNR for all tested lines was in a range of 22-25 dB. When investigating the effect of distillation on BER (Fig. 5 (b)), we see that the BER mirrored the trend in Q^2 - dropping and saturating at a BER below 10^{-2} when the OSNR was > 25 dB. The threshold of $Q^2 = 19.3$ dB in the Q^2 plot translates into a BER of 1.3×10^{-2} , where we see that the required OSNR was similar to that shown in the Q^2 plot. This indicates that the noise could still be considered a Gaussian distributed noise field contribution after distillation. For the GMI plot in Fig. 5 (c), the GMI exhibited a similar trend to Q^2 , levelling off at ~ 11.6 b/symbol. With the reference for Q^2 and BER as given in Fig. 5 (a), (b), this relates to the GMI limit of 11.4 b/symbol regarded as a 5% reduction of the ideal achievable information rates of 64QAM at 12 b/symbol. Again, the required OSNR to achieve this limit also coincided with that needed for the Q^2 and BER.

From the results presented in Fig. 5, we notice that if the OSNR of the tested lines is above 25 dB, the performance can exceed our benchmark of a 5% reduction in GMI. Therefore, we could regard OSNR = 25 dB as the lowest OSNR for our EO comb to achieve the benchmark without narrowband filtering for lines, which can be used to inform us of power requirements for optical frequency combs when used as carriers in optical communication systems.

B. Results with distillation

Figure 6 (a)-(c) shows that the performance of the system using the EO comb lines that were distilled (filtered) by the MRR improves significantly, as compared to the un-distilled case. Figure 6 (a)-(b) shows that all traces saturated at Q^2 values of almost 21 dB and a BER $< 9 \times 10^{-3}$ when the OSNR was > 20 dB. Moreover, all lines required just ~ 13 – 15 dB of OSNR to reach the limits. For the GMI plot in Fig. 6 (c), we see that GMI also penetrated the limit of 11.4 b/symbol at OSNR ~ 13 – 15 dB and began to flatten at a GMI of 11.6 once the OSNR was adjusted to > 17 dB.

The plots (Figs. 5 and 6) of these metrics clearly show that the improvement in performance realised when distilling comb lines with the MRR is significant, achieving up to 7 dB in Q^2 when comparing Figs. 5 and 6 for OSNR below 25 dB, i.e., where the optical noise dominates. However, once OSNR increases, the improvement is less noticeable since the optical noise plunges into the same level as transceiver noise which is the upper limit of the system. Moreover, one can also conclude that comb distillation can extend the transceiver noise dominated performance ~ 10 dB of OSNR as indicated in the difference of required OSNR at the 5% information reduction limits for both cases, (i.e. required OSNR ~ 22 – 25 dB for the bypassed case whereas 13–15 dB for the distilled case).

- *C. Comparing performance with and without distillation*

To gain further insight into the performance of the system in terms of OSNR, for $Q^2 = 19.3$ dB, we interpolated the Q^2 values from each comb line with and without distillation and solved the fitting equations for the required OSNR. Figure 7 shows that required OSNR is generally flat, with small fluctuations, for all frequencies. The average required OSNR at the limits for carriers with and without distillation are ~ 24 dB and ~ 15 dB, respectively, both varying by $\sim \pm 0.5$ dB. This implies a reduction of the required power per line by 9 dB, suggesting that one could either introduce more comb lines to support a larger overall optical bandwidth of the superchannel transmission, or lower the power of the seeding laser for the EO comb generation to reduce power consumption.

Using the average required OSNR of 15 dB for the distilled carriers as a benchmark, we fit the curve and interpolated GMI values at this OSNR for the two cases, to estimate the increase in achievable bit rate achievable by comb distillation. Figure 8 shows that the values for the narrowband filtered lines lie around the corresponding GMI limit of 11.4 b/symbol with a small fluctuation of ≤ 0.1 b/symbol, while for the un-distilled lines GMI values lie around GMI = 9.5 b/symbol with a larger variation of ~ 0.5 b/symbol. This indicates that distillation can improve GMI by about 2 bits/symbol for the 64QAM signals we investigated, showing that comb distillation can provide a real increase in achievable information rates for combs amplified from a low power seed.

In order to qualitatively visualize the impact of comb distillation, Fig. 9 shows the signal constellations for both distilled and un-distilled carriers, at an OSNR of 15 dB. Here, we see that the signal constellation for the distilled carriers exhibits clearly distinguished points with a small distribution arising from Gaussian distributed noise in the central part, with a noticeable increase in variance for the outer lying points. This contrast of variation with constellation point amplitude is more severe than the outer points in the case of un-distilled lines. This can be explained by the fact that all symbol points have the same level of OSNR, hence the further out from the origin the symbols are, the higher is noise level.

Demonstration Of Comb Distillation For Local Oscillators

In this section, we study the potential impact of comb distillation at the receiver side when applying the same approach as the previous section, to perform comb distillation for local oscillator (LO) lines.

- *A. Without distillation*

In this experiment we etc etc... Here, the comb lines were directly fed into the LO port of the coherent receiver, bypassing the MRR, while the ECL lines were used for carriers. We plot the traces of the performance metrics (Fig?) that reveal similar behaviour to the case of bypassed carriers, where all traces exhibit trends resulted from conventional noise loading. As seen in Fig. 10 (a)-(c), the traces saturate at the upper limits of $Q^2 \sim 20$ dB, with a BER $< 10^{-2}$, and a GMI of ~ 11.6 b/symbol when the OSNR reaches ~ 27 dB. When considering the 5% reduction in information rate limits, we required ~ 22 – 25 dB in OSNR for the LO lines to achieve this limit. These values of OSNR coincide with the benchmarked results from the bypassed carriers shown in Fig. 5. As a result, we conclude that deployment of noisy comb lines at

both the transmission and receiver sides after amplification sets the lower limit for per-line and total comb power.

- *B. With distillation*

To determine the benefits of distillation by the MRR for LO line narrowband filtering, we purified the tested comb lines before using them as LOs. Fig. 11 (a)-(c) show the performance of the system after distilling the LO lines. Here, it is seen that all metrics became flat at a $Q^2 \sim 20.5$ dB, with a BER $\sim 6 \times 10^{-3}$ when the OSNR was 20 dB, and for a GMI of 17 dB, at a 11.6 b/symbol after OSNR. Moreover, after comparing Fig. 11 (a) and Fig. 10 (a), we notice that the LO distillation can contribute to an improvement in the Q^2 by up to ~ 8 dB, especially in the optical noise dominated region (OSNR ~ 10 dB). When looking at the 5% reduction of information rates, the system required only 12-14 dB of OSNR to attain this limit. This reduced the required OSNR for the comb by ~ 12 dB compared with the bypassed case. Hence, we conclude that LO distillation helps the system achieve the transceiver noise limit faster, similarly to how carrier distillation does.

- *C. Comparing performance with and without distillation*

We next plot the required OSNR at a $Q^2 = 19.3$ dB for each tested frequency after interpolating each trace as shown in Fig. 12. We see that the bypassed LO lines possess an overall flat profile of required OSNR with average required OSNR at ~ 25 dB, conforming to that needed in Fig. 11 (a), with a variation of ± 0.5 dB while the distilled LO lines required just 13 dB with the same variation. This translates into a reduction of 12 dB in OSNR, suggesting that distillation could save the per LO line power by up to 15 times.

Comparing the required OSNRs for both carrier and LO distillation cases in Figs. 7 and 12, we conclude that narrowband filtering by the MRR tends to be more effective for comb lines deployed as LOs, rather than for carriers, since the OSNR benefits caused by the MRR can be up to 12 dB for the LOs, while they are only 9 dB for the carriers. Therefore, based on this we conclude that it is more important to emphasize the mitigation of noise for LOs.

To compare the information rate of both bypassed and purified LOs at the benchmarked OSNR = 13 dB, we plot the interpolated GMI at this OSNR of each line for both cases in Fig. 13. Again, we find similar patterns to the previous experiments where the GMI for the distilled LOs fluctuated around the 11.4 b/symbol limit with negligible deviation whereas GMI for the bypassed LOs was located well below ~ 8 b/symbol. This indicates that the gain in the achievable information rates is higher for a distilled LO, compared to the gain observed with a distilled carrier. We infer from this that the noise transfer through the LO is greater, possibly due to the constant high power of the local oscillator. We expect that noise transfer occurred via signal/LO beating in the coherent receiver.

We look qualitatively at the effects of LO distillation on the signal constellations. In Fig. 14, the constellation at an OSNR = 13 dB, after passing the LO lines through the MRR, appears to be a near ideal

constellation with a Gaussian distribution around the expected points due to noise. On the other hand, the constellation arising from the bypassed LO is quite noisy, especially at the edges of the constellation. This resembles the results from the cases of carrier lines in Fig. 9 with an exception for required OSNR which is 2 dB lower, again suggesting that comb distillation plays a more important role for the LOs than for the carriers.

Discussion

As we have observed, comb distillation by the MRR offers a reduction in the required OSNR by ~ 9 and ~ 12 dB for comb lines used as either carriers or LOs, respectively, at a threshold of 5% reduction in information rate, operating at 64QAM. These results could possibly be even better for low-level modulation schemes such as QPSK or 16QAM. This is because Euclidean distances between each symbol for these schemes are larger, causing the modulation formats to be more tolerant to errors than 64QAM, i.e., the schemes require lower OSNR to remain error-free ($\text{BER} \leq 10^{-3}$). Therefore, we expect the thresholds at which comb distillation becomes useful to increase for the simpler modulation formats.

While in these experiments we investigated comb distillation for separate cases where the comb lines were used as carriers and LOs, we could also study the system performance where the comb lines were distilled by the MRRs for both the carriers and LOs simultaneously. This may consist of two independent comb sources and two MRRs, enabling realistic comb-based superchannel transmission. We note that not only do the resonance peaks, but also the FSRs of both MRRs, need to strictly match each other to avoid a substantial frequency offset emerging for a significant number of modes relative to the central frequency [41]. This could still support high bandwidth transmission since high-frequency comb lines would still be able to be utilized.

To lower the optical noise further, higher Q MRRs ($Q \sim 10^8 - 10^9$), which are typically employed in nonlinear optics or microcomb generation [51]–[53], having resonance bandwidths on the order of 100 kHz or so, could be used to distill comb lines as their filter profiles can firmly fit the lines (linewidth ~ 100 kHz), resulting in almost laser-like lines after distillation. However, this approach would be more sensitive to any frequency mismatch between the resonance peaks and comb lines as a result of any dispersion in the MRRs, thus shifting the resonances from the equidistant grid, as illustrated in Fig. 15. Here, the comb lines match the equidistant grid shown as dashed lines. It is seen that the number of lines undergoing purification with narrow resonances is limited, since the comb lines cannot reside in the shifted resonance lobes (due to dispersion) and are thus attenuated by the stopband. However, with a trade-off in in-line noise, distillation by wider resonances would allow more comb lines to transmit through the drop port since the passband regions are wider, and so any detuning of the resonances due to chromatic dispersion would have less of an effect. This may be a reason why we do not observe limitations in our comb bandwidth (~ 1.3 THz) after distillation.

Although our approach can lead to substantial noise reduction for comb lines, it still has a limitation because the comb line spacing is required to match the fixed FSR of the MRR. This limits the flexibility of

the source to be used for transmission at an arbitrary symbol rate. As a result, one should explore other potential approaches that offer flexibility in line spacing. Two potential comb distillation options that are adaptable to variations in comb spacing are distillation via stimulated Brillouin scattering (SBS), or through optical injection locking (OIL).

SBS can be used for comb line purification since it requires just another replica of the initial comb to be shifted by the Brillouin frequency shift, and the initial comb lines are also amplified via SBS, enabling line filtering with a bandwidth of ~ 30 MHz [43], [44]. When scaling to many parallel lines, the flexibility to variations in line spacing comes at the cost of a high power required for the pump light, in turn needing careful consideration of the dispersion in the SBS shift. Scaling to high comb line counts may require multiple watts of optical power [43], [44], which increases when compensating for dispersion in the SBS shift [54].

The other approach for comb purification of optical injection locking (OIL), involves each comb line being injected into an individual slave laser so that the output frequency follows the line frequency. The approach can also support demultiplexing and amplification simultaneously by selecting the locking range to be smaller than the line spacing, so that only one line is amplified while the others are discarded [42]. With this principle, it has been reported [55] that low per-tone power combs can be amplified and used in optical communications systems, achieving better performance than the 'demultiplexing and amplification' method [55]. Similarly, scaling this approach to many parallel lines may have limitations, in that a new laser is required for each line, and each slave laser may also require stabilization to compensate any frequency drifts, e.g., OIL phase lock loop [56] or pilot tone assisted OIL phase locked loop [57].

Reflecting on these alternative techniques, if it is possible to precisely set the comb line spacing in an optical communication system, the high-Q filter distillation approach we investigate here may provide to be desirable in terms of energy efficiency and complexity. If only a small number of lines are required to be distilled, so that the energy consumption and relative complexity of SBS or OIL based approaches is minimal, then the comb spacing need not be precisely set and those approaches may be a preferred alternative.

Conclusion

We demonstrate an approach to reduce broadband noise centred around frequency comb lines, through the use of filtering with a high Q MRR. We test our approach with an EO comb and find that if the comb line spacing matches the FSR of the MRR, the narrowband filtering by the ring resonances can substantially reduce the optical noise. This is verified by our results for experiments where we use comb lines across a bandwidth where the required OSNR of the bypassed carriers is ~ 24 dB, while for the distilled ones is ~ 15 dB at a 5% reduction in information rate limit (GMI = 11.4 b/symbol). With the same threshold, bypassed LOs require an OSNR of ~ 25 dB, in contrast to the distilled LOs that require an OSNR of just ~ 13 dB. Given this ability to significantly reduce the noise and provide a high degree of

parallelism, this suggests that a high Q MRR could be included with chip-scale microcombs in order to simultaneously filter in-line noise of the microcomb lines before being deployed to support high bandwidth optical communications systems.

Declarations

Competing interests: The authors declare no competing interests.

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Figures

Figure 1

(a) Comb lines with high noise floor (black and red, left) and the drop port filter profile (blue, right), (b) Filtering by microring resonator. The filter profile superimposed on the noisy comb (left) produces a noise reduced “distilled” output (black and red, right).

Figure 2

two optical spectra measured with 12.5 GHz (0.1 nm) resolution, with an amplified (or noisy) comb depicted in blue and a distilled comb in magenta, for an overall comb bandwidth of ~ 1.3 THz.

Figure 3

(a) distilled/undistilled comb source, and demonstration when using the comb source as (b) carriers, (c) LOs; here ECL: External cavity laser, PM: Phase modulator, IM: Intensity modulator, PS: Phase shifter, OSA: optical spectrum analyzer, WSS: Wavelength selective switch, VOA: Variable optical attenuator, MRR: Microring resonator, AWG: Arbitrary waveform generator, DP-IQM: dual-polarization I/Q modulator, Coh. Rx.: Coherent receiver

Figure 4

Electro-optic frequency comb after attenuation and amplification with the red arrows representing the lines used in the experiment.

Figure 5

Overlay performance of all bypassed tested carrier lines in terms of (a) Signal quality factor, Q2, (b) BER, and (c) GMI, with dashed lines indicating limits of the 5% reduction of information rates in terms of the particular metrics

Figure 6

Overlay performance of all tested carrier lines with distillation by the MRR in terms of (a) Signal quality factor, Q2, (b) BER, and (c) GMI, with dashed lines indicating limits of the 5% reduction of information rates in terms of the particular metrics

Figure 7

Required OSNR at Q2 = 19.3 dB, for both bypassed and distilled carriers against frequency of comb lines.

Figure 8

GMI plot for distilled and bypassed carrier lines at OSNR of 15 dB with the limit of GMI = 11.4 b/symbol as indicated with the dashed line.

Figure 9

Signal constellations as a results of distilled and bypassed carrier lines at OSNR = 15 dB.

Figure 10

Overlay performance of all tested LO lines without distillation in terms of (a) Signal quality factor, Q^2 , (b) BER, and (c) GMI, with dashed lines indicating limits of the 5% reduction of information rates in terms of the particular metrics.

Figure 11

Overlay performance of all tested LO lines with distillation by the microring resonator in terms of (a) Signal quality factor, Q^2 , (b) BER, and (c) GMI, with dashed lines indicating limits of the 5% reduction of information rates in terms of the particular metrics.

Figure 12

Required OSNR at $Q^2 = 19.3$ dB, for both bypassed and distilled LOs against frequency of comb lines.

Figure 13

GMI plot for distilled and bypassed LO lines at OSNR of 13 dB with the limit of GMI = 11.4 b/symbol as indicated with the dashed line.

Figure 14

Signal constellations as a result of distilled and bypassed LO lines at OSNR = 13 dB.

Figure 15

Comb distillation by the MRR featuring a narrow bandwidth (top) and wide bandwidth (bottom) of resonances, where the comb lines are shown in black with noise floor in red and the equidistant grid is illustrated as the red dashed lines.