Overcoming low-power limitations on optical frequency combs using a micro-ring resonator

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Abstract: We show that filtering of an optical frequency comb with a high quality-factor ring resonator enables the use of amplified low power combs as a multi-wavelength source. This approach improves effective source OSNR by 10 dB.

1. Introduction

Optical frequency combs have provided the basis for multiple demonstrations of ultra-high capacity optical communication systems (e.g. [1-3]), by generating a broad bandwidth of high quality, laser-like optical carriers. These frequency combs can be generated from sources that scale in size from a benchtop device [1], down to a single optical chip [2,4]. Compact frequency comb sources generally rely on high quality-factor resonant structures, which when driven by a CW laser source, oscillate to provide a multitude of comb lines at a spacing defined by the resonator free-spectral range [5]. While these sources can provide high optical carrier-to-noise ratio optical carriers, as more carriers are generated, and as the frequency comb spectrum is shaped to provide uniform power for all carriers, per-carrier power is reduced. As such, these carriers generally require amplification before modulation in optical communication systems, introducing broadband noise. This noise limits the range of powers of usable comb lines, and so the performance of optical frequency combs in optical communications systems, becoming a major performance limiting factor in comb-based optical communication systems [6].

The same family of high quality-factor (typically $Q\sim10^6$) resonant structures used in compact frequency comb generation can act passively as periodic ultra-narrowband filters, with a bandwidth of 100-200 MHz. If the frequency spacing of the comb and the resonator are matched, this can then provide a reduction in broadband optical noise around the wanted comb lines, which can be used to improve carrier-to-noise ratio over the bandwidth of the optical channel. This approach has been used in high precision optical frequency comb metrology applications, and we use it here to distill wanted optical carriers out of broadband noise from amplification, as illustrated in Fig. 1.

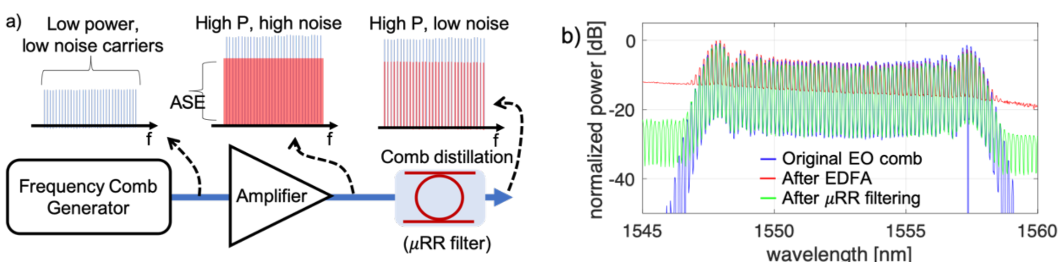

Figure 1 – a) Micro-ring resonator frequency comb distillation concept. A low power frequency comb is amplified, and wideband noise is added by this process. Filtering with a high quality-factor micro-ring resonator removes much of the broadband noise by simultaneously tightly filtering all carriers, leaving only a small residual in-band with the optical carriers. b) Comb spectra out of the comb generator (blue), after amplification (red) and after distillation (green). Shaping of ASE by the μRR can be seen outside the comb bandwidth, and reduction in noise spectral density over the resolution bandwidth (0.1 nm, 12.5 GHz) can be observed.

Here we show that filtering a frequency comb with micro-ring resonator (μRR) effectively improves comb carrier-to-noise ratio by 10 dB. This translates into a lowering of total required comb power before amplification of ~ 10 dB (from -15 to -25 dBm), enabling 64-QAM to be modulated on a carrier with a pre-distillation OSNR of 10 dB. This approach provides a path to low-power, energy efficient optical frequency combs being used to support applications that demand high optical signal to noise ratio and per-carrier power. Moreover, this shows a method for where micro-ring resonators enable high quality frequency combs without the need to oscillate.

2. Optical frequency comb distillation using a micro-ring resonator

For optical communications, the key properties of optical frequency combs are the available per-carrier (i.e. per-comb-line) power, carrier spacing and carrier-to-noise ratio. Carrier spacing determines whether high spectral efficiency superchannels can be supported through passive multiplexing from a single device [7]. Per-carrier power and carrier-to-noise ratio limit the modulation level achievable on these carriers [6, 8]. Integrated platforms, while providing a path to efficient optical comb generation, tend to provide low per-carrier power [4,5], and so need to be amplified before use, reducing carrier-to-noise ratio [6,7]. Alternative comb generation methods such as spectral broadening of a high-power pulse to provide many carriers, also tend to suffer from low carrier-to-noise ratio [8].

As such, techniques have been explored to improve carrier-to-noise ratio in optical frequency combs. Stimulated Brillouin Scattering has been used to improve carrier-to-noise ratio to enable higher order QAM modulation [8]. The bandwidth of the comb able to be distilled was limited by shifts in the Brillouin gain over the course of ~ 200 GHz. Injection locking to a micro-ring parametric oscillator has also been demonstrated [9], but this focused on distillation of a single line. Alternatively, high quality-factor optical cavities have been used to distil many carriers simultaneously for application to microwave signal generation and spectroscopy [10]. We follow this approach, using a high quality-factor Hydex micro-ring resonator (Q ~ 10^6) to reduce broadband noise after amplification of an electro-optically generated frequency comb [6], with the experimental set-up outlined in Fig. 1. The resonator is fiber coupled, and able to be stabilized using standard open-loop thermo-electric control, maintaining alignment to a standard external cavity laser (Keysight N7714A) over the course of days. A resonator quality-factor of 10^6 relates to an optical filter bandwidth of ~ 200 MHz, and the FSR of 19.5 GHz allows for high-order modulation for superchannel generation [7]. The original EO comb spectrum, spectrum after amplification at low input power, and spectrum after distillation are shown in Fig. 2b. The comb bandwidth is ~ 1.3 THz, and Fig. 1b shows distillation of all 68, 19.5-GHz-spaced comb lines.

3. Experiment & Results

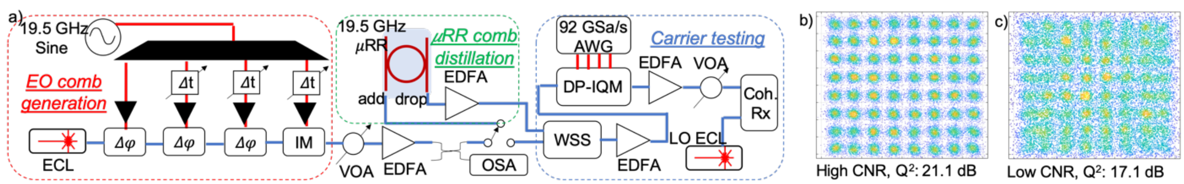

Figure 2 – a) Experiment set-up. ECL: External cavity laser, Δφ: phase modulator, IM: intensity modulator, Δt: variable RF delay line, VOA: Variable optical attenuator, Coh. Rx: Coherent receiver. Received constellations with b) high carrier-to-noise ratio, and c) when impaired by noise.

The experimental set-up is shown in Fig. 2. An electro-optic frequency comb is generated with three phase and one cascaded intensity modulator, run from a single tunable signal generator. The phase modulators with Vpi = 3V are each driven with a CTT Inc. APW/265-3335 amplifier, while the intensity modulator is used to carve out pulses, thereby flattening the comb spectrum. Alignment of the comb to the resonator was achieved by measuring the optical spectrum of optical noise passing through the resonator with a 150 MHz resolution optical spectrum analyzer (OSA). The comb is then attenuated before launch into an EDFA, with total power varied from -10 to -30 dBm, and output power set to 21 dBm. Comb OSNR is measured at this point with a standard OSA, with an 0.1 nm measurement bandwidth. Fig. 2 b&c show indicative constellation diagrams, illustrating that when OSNR is degraded, the outer constellation points are affected more. This is due to the fact that the individual constellation point amplitude-to-noise ratio is the same, as in this case the carrier is pre-distorted before modulation.

The comb then either passes through the micro-ring resonator, or bypasses this, before filtering with a 10 GHz band-pass filter used to select a single test carrier, before amplification to 14 dBm before modulation. The μRR is a double-bus connected ring, enabling us to access the drop port of the device for filtering, and is fiber-pigtailed for ease of use. The test carrier is modulated with a 35 GHz bandwidth dual-polarization I/Q modulator (DP-IQM), driven by a 92 GSa/s AWG (Keysight). Signal quality is then directly measured using a 25 GHz bandwidth coherent receiver digitized by a 33 GHz bandwidth, 128 GSa/s oscilloscope (Keysight UXR). We modulate 64-QAM, 1% RRC shaped at 19 Gbaud, which is compatible with superchannel generation from this source.

Fig. 3a shows measured signal quality-factor (Q^2) against comb OSNR, with and without the micro-ring resonator in place for comb distillation, while Fig. 3b shows BER against comb OSNR, both of a comb line carrier at 193.089 THz. Q^2 is extracted directly from measured error vector magnitude (EVM) as $Q^2 = 1/EVM^2$. Back-to-back signal quality-factor was limited to near 22 dB due to transceiver noise, both in the case where either an ECL, or an amplified comb line, was used as a carrier. When bypassing the micro-ring filter, performance of the line at 193.089 THz reduced by about 1 dB after a change of OSNR by 5 dB. When using the micro-ring to distill the comb before modulation, a 1dB penalty was measured after reducing OSNR by 12 dB. To reach Q^2 =19 dB (1.5e-2 BER, assuming Gaussian noise), 11 dB and 22 dB comb line OSNRs are required for the micro-ring distilled and bypassed carriers, respectively. Using a BER of 2.2e-2 as an indicative performance threshold on Fig. 3b (related to a 20% soft-FEC threshold), require comb line OSNR is reduced by 9.5 dB. Through analysis of the optical spectrum, we estimate that these OSNRs relate to required-per-carrier powers of -45.5 and -36 dBm before amplification, with and without distillation respectively. We also benchmark performance of a set of carriers across the generated comb, with the required carrier OSNR for our chosen error threshold plotted against carrier frequency in Fig. 3c. We find that the required OSNR varies by only ±1 dB, indicating that the μRR is capable of distilling many carriers simultaneously.

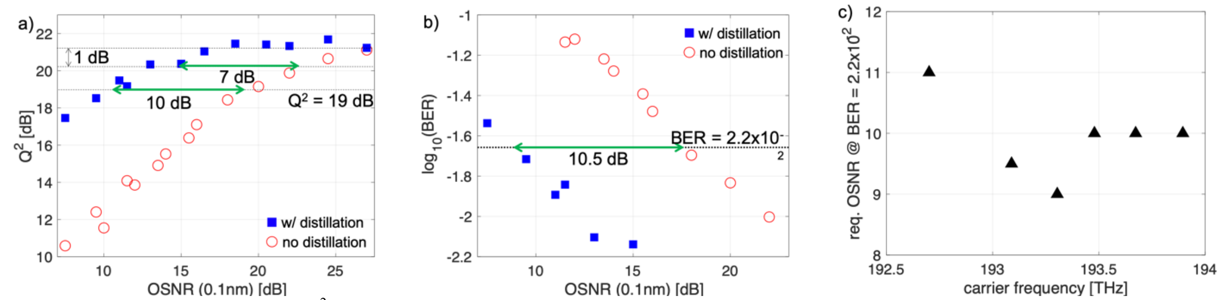

Figure 3 – a) Signal quality-factor (Q^2) against measured carrier OSNR (0.1nm res. BW), b) bit-error rate against measured carrier OSNR, c) required OSNR for a range of carriers after distillation, evaluated at BER = $2.2\text{x}10^{-2}$.

4. Discussion and Conclusion

Narrowband filtering serves to remove excess out-of-band noise in the distilled case, enabling high order QAM modulation on low carrier-to-noise ratio frequency combs. The micro-ring resonator used in this experiment has a fixed FSR, meaning that the comb must be matched to the FSR. If the initial comb is provided by a micro-resonator, placing a broadband comb generation ring and filtering ring with matched FSRs on a single chip device may be feasible. Distillation via Brillouin scattering can in principle avoid this limitation, as SBS is a parametric effect, but may require prohibitively high power to scale to tens or hundreds of comb lines.

We note that waveguide chromatic dispersion will eventually limit the bandwidth over which a micro-ring can provide comb distillation, as FSR changes with wavelength. We did not observe this effect over the terahertz bandwidth investigated here. Comparing our improvement in required comb line OSNR of ~ 10 dB to estimation of individual comb line power given for bright solitons in [6], we may expect an increase in the number of useable comb lines by a factor of over 3x, suggesting that a C-band comb may be extended to cover S, C and L bands. Moreover, a 10 dB OSNR improvement allows a further 10x power split, which may be useful for single-source, high-capacity SDM.

In conclusion, we demonstrated the use of a micro-ring filter to overcome comb-line power limitations when using optical frequency combs in coherent communication systems. We observed a reduction in the required OSNR by over 10 dB at an indicative BER threshold, reducing the required pre-amplification comb line power to -45.5 dB from -36 dB. Comparing a 1dB Q^2 penalty from maximum measured performance, the required OSNR was reduced from 22 dB to 15 dB. This demonstration provides a method to expand the useable power range, and hence bandwidth, of frequency combs as massively parallel sources for optical communications systems.

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3. References

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