Kerr combs for Single-Span Long-Haul Analog Optical Links

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We utilize a single soliton generated in a SiN microring resonator for stimulated Brillouin scattering mitigation in a 50 km link. A 9.1 dB increase in threshold power relative to the CW case is obtained. Potential improvements of the results using dark pulses are discussed.

Keywords—Frequency combs, microwave photonics.

I. Introduction

Frequency combs have revolutionized the field of metrology and its applications extends to numerous fields such as vibrational molecular spectroscopy, astronomical spectrograph calibration, ranging and optical communication. A remarkable miniaturization of frequency comb sources was achieved using high quality factor microresonators [1]. The resonant enhancement of a continuous-wave (CW) pump and tight confinement of light in a small volume leads to high intensities allowing broadband nonlinear conversion. In the past few years, extensive efforts have been devoted towards understanding this nonlinear process and controlling the comb generation to obtain mode-locked, coherent comb states. As the understanding of Kerr combs is approaching maturity, the demonstrations of Kerr comb applications are rapidly growing. In particular, Kerr combs have been used in a variety of digital optical communication experiments, demonstrating capability for massively parallel wavelength-division multiplexing [2] and advanced modulation formats up to 64-QAM [3]. With growing interest in radio over fiber for 5G networks, analog photonic links, too, can benefit from Kerr combs. In long-haul analog optical links, stimulated Brillouin scattering (SBS) limits the maximum optical launch requiring the use of mid-span amplifiers. This, however; drives the link noise figure significantly above the shot noise limit, which is detrimental for applications such as antenna remoting that has stringent noise requirements. Using an electro-optic (EO) comb as the optical carrier, researchers in [4] circumvented the SBS lunch power limitation by redistributing the optical carrier power over the comb lines. Low noise and highly stable broadband Kerr combs are an attractive alternative to EO-combs. With recent studies using Kerr comb based true time delay for microwave beamforming [5], microcombs can be a valuable tool for next generation analog photonic links.

In this paper, we perform a preliminary experiment using a single cavity soliton as an optical carrier for a 50 km link based on an externally intensity-modulated direct detection link architecture. Finally, we discuss potential improvement of the results using a dark pulse with a lower repetition rate.

II. Experimental results

The experimental setup is shown in Fig. 1a. The CW pump at ~1551 nm is amplified, and the ASE is filtered out using a DWDM filter. The power before the microring is ~ 640 mW. After the microring, two DWDM filters are used to attenuate the strong pump line. Subsequently, the comb is sent to an intensity modulator (IM) biased at quadrature. The IM is followed by a pulse shaper and an amplifier. The link consists of a 50 Km spool of single mode fiber (SMF) followed by dispersion compensation fibers (DCF). To measure the link gain, a post-link amplifier is added to get 7 mA from a photodiode with a 3-dB bandwidth of 17 GHz. The pulse shaper is used to cancel any residual dispersion not compensated for by the commercial DCF link. Note that in our current results, no amplitude shaping was applied in the pulse shaper. The silicon nitride microring resonator has a radius of 100 μm corresponding to free spectral range (FSR) of ~227.5 GHz. The width of the ring is 2 μm, and its thickness is 790 nm leading to anomalous dispersion. The resonance has a loaded quality factor of 1 million. The pump laser is tuned into resonance until a stable comb comprising a single cavity soliton is obtained. The spectrum before and after the link is normalized and overlaid in Fig.1 (c).

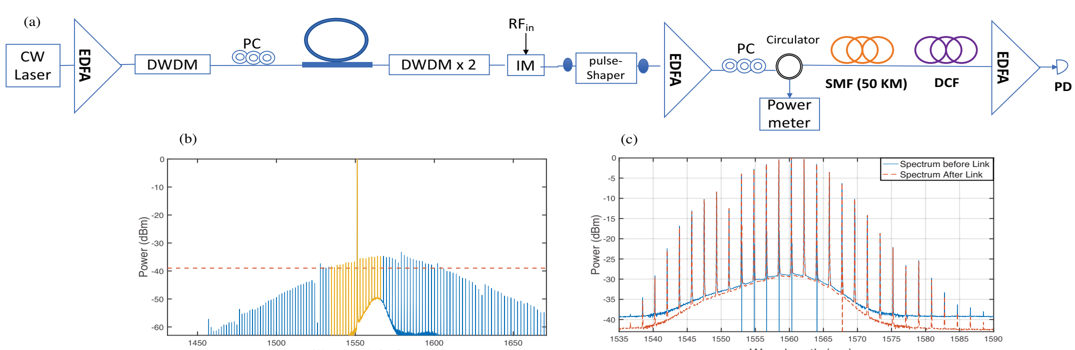

Fig. 1. (a) Experimental setup. (b) Single soliton spectrum (without DWDM filters); the wavelength region from 1535 nm to 1565 nm is highlighted in yellow. (c) Normalized spectrum before and after the link, with 13 dBm launch power.

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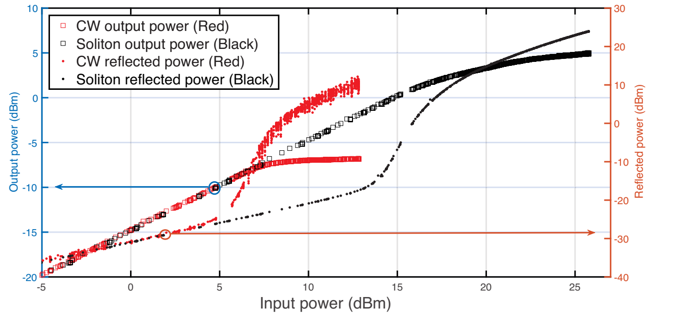

Fig. 2. The input power to the link versus the back reflected power (right y-axis) and the output power (left y-axis) for the CW (red) and Kerr comb soliton (black).

First, we measure the SBS threshold for the CW case. The reflected and output power after the ring are shown in Fig.2. We measure an SBS threshold power of 4.7 dBm. For the single soliton case, the SBS threshold is 13.8 dBm. The output power plateaus after the onset of SBS; the maximum output power is more than 10 dB higher with the comb compared to a single frequency input. Fig. 3 shows the link's small signal gain with and without the pulse shaper used for residual phase compensation. The two cases begin to differ after 10 GHz reaching a 2-dB difference at 16 GHz. The important point is that the dispersion is compensated sufficiently to avoid degradation of the link response. About 9 dB of the roll off in the measured response at 17 GHz is due to the electro-optic components and photodetector.

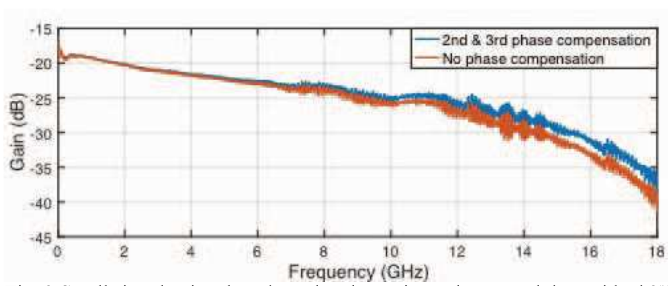

Fig. 3 Small signal gain when the pulse shaper is used to cancel the residual 2nd & 3rd order dispersion (blue), and no residual phase compensation (orange).

While the 9.1 dB increase in threshold power is significant, better results should be achievable with a flattened spectrum. Brillouin suppression is expected to scale with number of optical lines, assuming they have equal intensity. A flat spectrum allows launching more average power before reaching the threshold. However, the low conversion efficiency of the Kerr comb generation process is a concern, as the need for a strong pre-link amplifier is expected to lead to deteriorated link noise figures. For the single soliton, the percentage of total power in all comb lines excluding the pump is 1.1% (~ 2 mW). If the wavelength region in the C-band between 1535 nm and 1565 nm is flattened to -39 dBm (horizontal dashed line in Fig.1 b), the percentage is 0.24% (0.65 mW). Additional improvement can be readily obtained using a ring with smaller FSR, which will provide more comb lines within a fixed optical bandwidth. However, obtaining a single soliton in SiN microresonators with FSRs lower than 100 GHz - while possible - remains practically challenging. To address these concerns, we expand our scope to other Kerr comb solutions.

Dark pulses can be generated with high efficiency in normal dispersion microrings by the aid of mode-interaction [6]. Using a ring with a 2 µm width and 600 nm thickness, we demonstrate the generation of a dark pulse with 73 GHz FSR. A CW pump at 1562 nm with 1 W of power before the chip is used. The transition into resonance goes through a chaotic region and evolves into a coherent state as shown in Fig. 4. Since the conversion efficiency is high and no large drop in the intracavity power occurs, thermal effects do not impose any serious restrictions on detuning. The coherent state can be accessed easily via manual detuning. The conversion efficiency of the dark pulse is far superior to single solitons. The percentage of total output power in all comb lines excluding the pump is 49% (~139 mW). If the wavelength region in the C-band is flattened to -27 dBm (horizontal dashed line in Fig.4 b), the percentage is 3.1% (8.4 mW). An order of magnitude improvement in conversion efficiency is attained even after spectral flattening. The number of lines in the C-band with equal power after flattening is 30 lines, which results in a minimum expected increase in SBS threshold power by 14.7 dB. More lines will be available for even stronger Brillouin suppression if C+L band components are used.

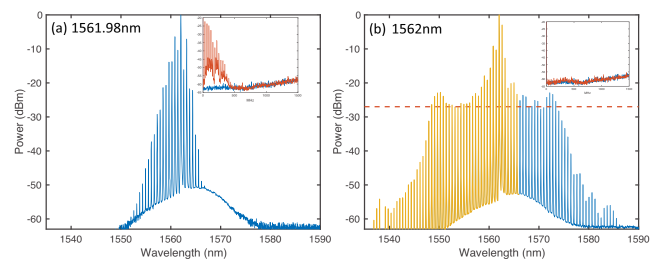

Fig. 4. The transition into a coherent dark pulse as the wavelength is increased. The inset shows the RF noise in orange and the measurement floor in blue. The C-band in (b) is highlighted in yellow.

III. Conclusion

Preliminary experiments using Kerr comb solitons for SBS mitigation in long haul is performed, and a 9.1 dB increase in Brillouin threshold power is obtained. In the future, we hope to improve our results by using the spectrally flattened dark pulse with 3× lower repetition rate. Furthermore, by optimizing the components and the detection setup, we expect to achieve improved link performance, e.g., higher and flatter RF gain.

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