Enhanced Coherent Communications with Brillouin Amplifiers

Mark Pelusi[(1)], Takashi Inoue[(1)], Shu Namiki[(1)]

(1) Platform Photonics Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki. Japan. m.pelusi@aist.go.jp.

Abstract *Application of Brillouin amplification for enabling higher performance coherent communications with higher-order QAM signals is presented. Capabilities and limits for using the uniquely narrow gain bandwidth to suppress out-of-band spectral line noise for carrier recovery at the receiver from lower power pilot tones are described.*

Introduction

Brillouin amplification with its characteristic narrow gain bandwidth in the tens of megahertz range is well suited to applications where current commercial optical bandpass filters (BPF) with typical minimum gigahertz bandwidth limitation don't suffice. Examples are for tailoring frequency combs[1-3] like for metrology[4]. Its potential benefit to noise sensitive coherent communications with advanced modulation format signals has also been investigated. Here, despite its general incompatibility as a low noise, broadband signal amplifier, it can aid processing light sources used for signal generation, detection and regeneration. Examples are for signal carriers derived from frequency combs at the transmitter[5] or for carrier recovery at the receiver from pilot tones that are multiplexed with the signal[6-10]. The latter has been shown for self homodyne style detection[6-9] in place of a conventional local oscillator (LO) laser, as well as Kramers-Kronig detection[10]. It has also assisted signal regeneration based on phase sensitive amplification with four wave mixing by selectively extracting phase coherent spectral lines for the required pump sources[11].

The compatibility of Brillouin amplification with more noise sensitive 64-QAM signal coherent communications has also been investigated. Despite a general reputation as being noisy compared to conventional optical amplifiers such as EDFAs, the narrow gain bandwidth enabled significantly enhanced carrier to noise ratio (CNR) of spectral lines by suppressing background noise in relative power. This was shown to in turn enable significantly higher demodulated signal performance when applied to noisy frequency combs serving as signal carrier sources at the transmitter[5], or noisy pilot tones at the receiver for carrier recovery before coherent detection[8],[9], like potential of a BPF[12].

Although recent advances in narrow BPF's with micro-ring resonators has demonstrated similar functionality[13], the broader bandwidths in the hundreds of megahertz range limit its capabilities. While sub-100 Hz bandwidth has been reported[14], high insertion loss as opposed to gain and required tracking and alignment of the narrow passband to the typical random frequency fluctuations of standard lasers are challenges.

In this paper, the performance enhancement capabilities of Brillouin amplification for 64-QAM coherent communication is presented, based on our latest report[9]. For pilot tone carrier recovery, this is predicted to permit up to ≈24 dB lower pilot tone to signal power ratio (PSR) for maintaining comparable performance than without, and a minimum tolerable PSR for maintaining a bit error rate (BER) below the hard decision FEC limit near −40 dB. The influence of Brillouin noise and its minimization are also considered. The results highlight that rather than an impediment, Brillouin amplifiers can deliver significant performance benefit to advanced coherent communications.

CNR enhancement limits

The benefit of the narrowband Brillouin gain for background noise suppression is illustrated in Fig. 1 as prior [5],[8],[9]. The input spectral line can be a frequency comb line or a pilot tone with initial CNR at the input to the Brillouin amplifier (CNR_{IN}) determined by the assumed uniform background noise level of density, S_C. This is contained over the relevant signal spectrum channel width, $\triangle_S$. After Brillouin gain G, in narrow bandwidth, $\triangle_B$, the relative power of out of band noise is suppressed. Brillouin noise is also added and approximated as having uniform density S_B within $\triangle_B$. The influence of a realistic Lorentzian or Gaussian gain profile is expected diminished in the relevant case to optical communications of $\triangle_B \ll \triangle_S$. From this simplified representation, the maximum achievable CNR enhancement factor of $\triangle CNR = CNR_{OUT}/CNR_{IN}$ was straightforwardly estimated as $\triangle CNR_{LimSc} = \triangle_S \cdot G/[\triangle_S + \triangle_B \cdot (G-1)]$ when $S_C \gg S_B$. i.e. initial spectral line noise dominates over Brillouin noise[9]. Furthermore, when $G \rightarrow \infty$, then $\triangle CNR_{LimG\rightarrow\infty} = \triangle_S / \triangle_B$. For parameters relevant to experiments with $\triangle_B \approx 30$ MHz, signal $\triangle_S \approx 9.6$ GHz, and moderate $G = 30$

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

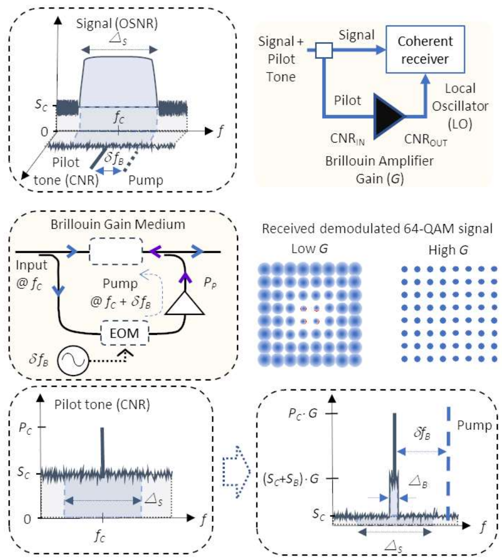

Fig. 1: Schematic of carrier to noise ratio enhancement with narrowband Brillouin amplification in application to carrier recovery from a pilot tone multiplexed with a signal.

dB, then $\triangle CNR_{LimSc} \approx$ 24 dB. Notably, this is near $\triangle CNR_{LimG\to\infty} \approx$ 25 dB, meaning only marginal benefit is predicted for G » 30 dB. Excessive G also has the drawback of increased S_B[15],[16]. The assumed S_C » S_B is approximately satisfied as S_B / $S_C \approx$ 0.1 for $CNR_{IN} \approx$ 5 dB/0.1 nm[8]. That is, with S_B estimated from the characterized $CNR_{OUT} \approx$ 40 dB at 30 dB gain in case of input of a low noise CW laser[16], and S_C from CNR_{IN} considering an input carrier power of ≈-13 dBm.

For experiments in this paper with an 8 Gbaud 48 Gb/s single polarization (SP) 64-QAM signal, the target CNR_{OUT} for achieving a BER below the hard decision FEC limit of 4.5×10^{-3} was ≈24 dB/0.1 nm[8],[9]. This was characterized by intradyne detection of the signal with a CW laser serving as the LO that was noise loaded with EDFA ASE to vary its CNR[9]. It thus follows the minimum potential CNR_{IN} for achieving BER < FEC limit with G = 30 dB i.e. $CNR_{OUT} = CNR_{IN} + \triangle CNR_{LimSc}$ >24 dB is CNR_{IN} > ≈0 dB/0.1 nm[8],[9].

For higher CNR_{IN} on the other hand, S_B/S_C grows larger and S_B becomes influential in reducing $\triangle CNR < \triangle CNR_{LimSc}$[8],[9]. It ultimately caps the maximum achievable CNR_{OUT} ≈40 dB at 30 dB gain[8],[9], meaning degradation is expected for CNR_{IN} >≈40 dB/0.1 nm. This was characterized for optimized operating conditions described in later sections. Favourably, although noise figure for Brillouin amplifiers is generally worse than for conventional EDFAs, near similar low noise has been shown attainable for input of spectral lines[17], rather than broadband signals.

Pilot tone carrier recovery limits

The approximate analysis was also extended to pilot tone carrier recovery. In this case, the demodulated signal performance at the receiver is now degraded by both low CNR of the pilot tone in addition to low optical to signal to noise ratio (OSNR). An overall effective OSNR at the receiver is thus defined as $OSNR_{EFF}$, whereby $OSNR_{EFF} \approx$ OSNR for OSNR « CNR, and $OSNR_{EFF} \approx$ CNR for CNR « OSNR. i.e. $OSNR_{EFF}$ converges to the dominant degradation. A relevant parameter is PSR. Usually a minimum PSR is desirable for both maximizing power in the signal and avoiding potential for nonlinear mixing in optical fiber link transmission. The relation of OSNR, PSR and CNR_{IN} is straightforwardly given by CNR_{IN} = OSNR + PSR in decibel units[9], for a pilot tone with only a carrier at f_C. Thus, the previously described $\triangle CNR_{LimSc}$ ≈24 dB at 30 dB gain is expected to equivalently enable up to ≈24 dB lower tolerable PSR for maintaining similar performance than for without. Thus, in case of high OSNR = 40 dB/0.1 nm at the receiver, then without Brillouin amplification, $OSNR_{EFF} \approx CNR_{IN}$ >24 dB/0.1 nm for BER > FEC limit requires PSR > -16 dB. On the other hand, with 30 dB Brillouin gain, this reduces by ≈24 dB to ≈-40 dB.

Brillouin amplifier operations

Brillouin amplification was implemented like Fig.1 with 4.46 km standard single mode fiber (SSMF) as the gain medium and a backward propagating pump spectral line with its frequency upshifted by $\delta f_B \approx$ 11 GHz from the input at f_C. While the pump can be another CW laser, its feedback frequency control can be needed[2],[18] to track typical laser random relative frequency drift that can be of a similar magnitude to $\triangle_B$ itself. Without it, output intensity can fluctuate whenever the gain peak frequency deviates from f_C, like for narrow BPF's.

Workaround alternatives can use a pilot tone to optically injection lock a pump laser as the slave[6],[7],[11], or just directly source the pump from the input by its electro-optic modulation followed by a BPF[19], or even single sideband modulation without a BPF[20]. The latter were originally shown for CW laser input. For experiments in this work, single sideband modulation implemented with an IQ modulator[21] was used. The later described experiments effectively seeded the pump this way, even for extreme cases of poor pilot tone CNR_{IN} as low as ≈2 dB/0.1 nm. Since near ≈30 dB gain was attainable with moderate pump power ≈14 dBm, one EDFA sufficed in the set-up.

Lowest noise was characterized as requiring an input power >≈-13 dBm, and ≈14 dBm pump power giving ≈30 dB gain[16]. Also required was optimized pump state of polarization (SOP) and frequency for peak gain. Deviating the pump SOP not only reduced gain, but also excited amplitude oscillations at a rate of tens of kilohertz[16], likely linked to the pump polarization pulling effect[22]. At higher pump powers, the oscillation grew stronger in amplitude and higher in frequency. At optimum SOP, the oscillations vanished.

Frequency detuning gave rise to a frequency dependant amplitude and phase distortion visible in virtual signal constellations[16], and similar to that seen in experiments for QPSK signals[11]. This is likely linked to the Kramers-Kronig relations for Brillouin gain[23] and a frequency dither potentially linked to that of the source[24], or induced on the gain peak frequency itself[25].

Pilot tone carrier recovery evaluations

The benefit of Brillouin amplification for pilot tone carrier recovery was investigated for a WDM three channel 48 Gb/s SP-64-QAM signal with 50 GHz channel spacing. In this case, the pilot tone was polarization multiplexed with the signal at the transmitter, as performed previously without Brillouin amplification[26],[27] and transmitted through an 80 km link of SSMF. At the receiver, it was then demultiplexed from the signal and input to the Brillouin amplifier for CNR enhancement before serving as LO for coherent detection of the signal. Here, the Brillouin amplifier enhanced the CNR for all WDM channel pilot tones simultaneously, with a total pump power scaled to the number of channels. A BPF at its output extracted the spectral line for detection of the selected WDM channel. The scalability to simultaneously amplify ≈40 spectral lines with narrow 10 GHz channel spacing was previously shown for frequency comb sources[5].

Pilot tone carrier recovery was evaluated for low PSR ≈-20 dB. This compares to typical PSR ≈-10 dB for optical injection locking method[28]. The spectra of the WDM signals and pilot tones for with and without Brillouin gain at total pump power of ≈20 dBm are shown in Fig. 2(a). Broad suppression of background noise is evident. The 64-QAM constellation of the center channel is shown in Fig. 2(b) in case of optimum overall launch power to the 80 km link of 0.6 dBm where BER was minimized at OSNR ≈33 dB/0.1 nm. The Q^2-factor was degraded by only ≈0.5 dB from the reference case of a low noise laser as the LO for the coherent receiver. That is, without pilot tones or Brillouin amplifiers and the laser input to the receiver via a polarization maintaining EDFA.

At this optimum power, CNR_{IN} was measured to be ≈10 dB/0.1 nm, and so well above the predicted minimum needed of ≈0 dB/0.1 nm for achieving BER < FEC limit. Also, due to growing influence of S_B on reducing $\triangle CNR_{LimSc}$ <24 dB at 30 dB gain, the reduced CNR_{OUT} combined with OSNR gave predicted $OSNR_{EFF}$ ≈30 dB/0.1 nm compared to ≈33 dB/0.1 nm for the reference case, accounting for the small degradation.

For a lower link launch power of ≈-8 dBm, the OSNR was degraded to 25 dB/0.1 nm - close to the FEC limit for the 64-QAM signal. Here, CNR_{IN} was measured to be ≈2 dB/0.1 nm, consistent with calculation from CNR_{IN} ≈OSNR + PSR – 3 dB, where the added 3 dB factor accounts for the pilot tone now including a power equalized pump tone in addition to the carrier[8],[9]. Without Brillouin amplification, signal demodulation at the receiver failed for such low CNR_{IN}. On the other hand, with 30 dB Brillouin gain, a BER just above the FEC limit was attained, near the expectation for the predicted $OSNR_{EFF}$ ≈23 dB/0.1 nm[9].

At the other extreme of larger link launch power above the optimum where OSNR exceeded ≈33 dB/0.1 nm, BER for both reference case and Brillouin amplified pilot tone converged. This was explained by nonlinear distortion in the 80 km transmission link becoming dominant. Without it, the growing influence of S_B is expected to lower $\triangle$CNR and limit CNR_{OUT} and $OSNR_{EFF}$.

Returning to the optimum link launch power point for minimum BER with measured OSNR ≈ 33 dB/0.1 nm and CNR ≈10 dB/0.1 nm, the expected lower limit on PSR for maintaining BER < FEC limit was estimated to be >≈-30 dB. That is, from PSR = CNR_{IN} – OSNR +3 dB with CNR_{IN} >≈0dB/0.1nm such that 30 dB Brillouin gain gives $OSNR_{EFF}$ ≈CNR_{OUT} ≈24 dB. Furthermore, in case of no 80 km link transmission, then the best case OSNR ≈40 dB/0.1 nm would raise this to ≈-37 dB.

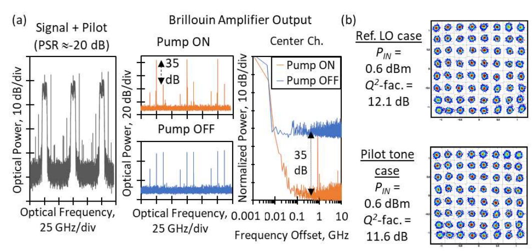

Fig. 2: WDM Brillouin amplified pilot tone as reported[8],[9] for coherent detection of WDM 3×48 Gb/s-SP-64-QAM signal. (a) Spectra (RBW = 5 MHz), and (b) constellations.

Summary

The benefit of Brillouin amplification for coherent communications with 64-QAM signals was presented. By its narrow gain bandwidth suppressing background noise, application to optical carrier recovery from pilot tones at the receiver relaxed the performance tolerance to lower pilot tone to signal power ratio than without. For realistic Brillouin amplifier parameters, this was estimated as being by up ≈24 dB reduction to near ≈-40 dB in case of high OSNR ≈40 dB/0.1 nm at the receiver, highlighting its advantages.

References

[1] F. Rohde, E. Benkler, and H. Telle, "High contrast, low noise selection and amplification of an individual optical frequency comb line", *Opt. Lett.*, vol. 38, no. 2, pp. 103-105, 2013.

[2] H. Al-Taiy, N. Wenzel, S. Preußler, J. Klinger, and T. Schneider, "Ultra-narrow linewidth, stable and tunable laser source for optical communication systems and spectroscopy", *Opt. Lett.*, vol. 39, no. 20, pp. 5826-5829, 2014.

[3] W. Wei, L. Yi, Y. Jaouën, and W. Hu, "Bandwidth-tunable narrowband rectangular optical filter based on stimulated Brillouin scattering in optical fiber", *Opt. Express*, vol. 22, no. 19, pp. 23249-23260, 2014.

[4] J. Subías, C. Heras, J. Pelayo, and F. Villuendas, "All in fiber optical frequency metrology by selective Brillouin amplification of single peak in an optical comb", *Opt. Express*, vol. 17, no. 8, pp. 6753-6758, 2009.

[5] M. Pelusi, A. Choudhary, T. Inoue, D. Marpaung, B.J. Eggleton, K. Solis-Trapala, H. Nguyen Tan, and S. Namiki, "Low noise frequency comb carriers for 64-QAM via a Brillouin comb amplifier", *Opt. Express*, vol. 25, no. 15, pp. 17847-17863, 2017.

[6] A. Lorences-Riesgo, M. Mazur, T.A. Eriksson, P.A. Andrekson, and M. Karlsson, "Self-homodyne 24x32-QAM superchannel receiver enabled by all-optical comb regeneration using Brillouin amplification", *Opt. Express*, vol. 24, no. 26, pp. 29714-29723, 2016.

[7] Y. Cao, M. Ziyadi, A. Almaiman, A. Mohajerin-Ariaei, P. Liao, C. Bao, F. Alishahi, A. Fallahpour, B. Shamee, A.J. Willner, Y. Akasaka, T. Ikeuchi, S. Wilkinson, C. Langrock, M.M. Fejer, J. Touch, M. Tur, and A.E. Willner "Pilot-tone-based self-homodyne detection using optical nonlinear wave mixing", *Opt. Lett.*, vol. 42, no. 9, pp. 1840-1843, 2017.

[8] M. Pelusi, T. Inoue and S. Namiki, "Enhanced carrier to noise ratio by Brillouin amplification for optical communications", *J. Lightwave Technol.*, vol. 38, no. 2, pp. 319-331, 2020.

[9] M. Pelusi, T. Inoue, and S. Namiki, "Pilot tone power limits of Brillouin amplified carrier recovery for optical communications," *J. Lightwave Technol.*, vol. 39, pp. 960-976, 2021.

[10] Q. Zhang, B. Zheng, and C. Shu, "Kramers-Kronig detection with Brillouin-amplified virtual carrier", *Opt. Lett.*, vol. 43, no. 6, pp.1367-1370, 2018.

[11] A. Almaiman et al., “Phase-sensitive QPSK channel phase quantization by amplifying the fourth-harmonic idler using counter-propagating Brillouin amplification”, *Opt. Commun.*, vol. 423, pp. 48–52, 2018.

[12] M. Sjodin, P. Johannisson, M. Karlsson, Z. Tong and P.A. Andrekson, “OSNR requirements for self-homodyne coherent systems”, *IEEE Photonic Tech. L.*, vol. 22, no. 2, pp. 91-93, 2010.

[13] B. Corcoran, C. Prayoonyong, A. Boes, X. Xu, M. Tan, S.T. Chu, B.E. Little, R. Morandotti, A. Mitchell, and D.J. Moss, "Overcoming low-power limitations on optical frequency combs using a micro-ring resonator," in *Proc. Optical Fiber Communication Conference (OFC)*, paper T4G.5, 2020.

[14] C. Taddei, L. Zhuang, C.G.H. Roeloffzen, M. Hoekman and K. Boller, "High-selectivity on-chip optical bandpass filter with sub-100-MHz flat-top and under-2 shape factor," *IEEE Photonic Tech. L.,* vol. 31, no. 6, pp. 455-458, 2019.

[15] M.F. Ferreira, J.F. Rocha, and J.L. Pinto, “Analysis of the gain and noise characteristics of fibre Brillouin amplifiers”, *Opt. Quant. Electron.*, vol. 26, pp. 35–44, 1994.

[16] M. Pelusi, T. Inoue and S. Namiki, "Brillouin amplifier noise characterization by a coherent receiver and digital signal processing," *J. Lightwave Technol.*, vol. 38, no. 16, pp. 4221-4236, 2020.

[17] M. Junker, M.J. Ammann, A.T. Schwarzbacher, J. Klinger, K.U. Lauterbach and T. Schneider, "A comparative test of Brillouin amplification and erbium-doped fiber amplification for the generation of millimeter waves with low phase noise properties", *IEEE T. Microw. Theory*, vol. 54, no. 4, pp. 1576-1581, 2006.

[18] Y. Souidi, F. Taleb, J. Zheng, M. Lee, F. Burck, and V. Roncin, "Low-noise and high-gain Brillouin optical amplifier for narrowband active optical filtering based on a pump-to-signal optoelectronic tracking", *Appl. Opt.*, vol. 55, no. 2, pp. 248-253, 2016.

[19] M. Niklés, L. Thevenaz and P.A. Robert, “Brillouin gain spectrum characterization in single-mode optical fibers”, *J. Lightwave Technol.*, vol. 15, no. 10, pp. 1842-1851, 1997.

[20] A. Loayssa, R. Hernández, D. Benito, and S. Galech, "Characterization of stimulated Brillouin scattering spectra by use of optical single-sideband modulation", *Opt. Lett.*, vol. 29, no. 6, pp. 638-640, 2004.

[21] B. Hraimel, X. Zhang, Y. Pei, K. Wu, T. Liu, T. Xu, and Q. Nie, "Optical single-sideband modulation with tunable optical carrier to sideband ratio in radio over fiber systems," *J. Lightwave Technol.*, vol. 29, no. 5, pp. 775-781, 2011.

[22] A. Zadok, E. Zilka, A. Eyal, L. Thévenaz, and M. Tur, "Vector analysis of stimulated Brillouin scattering amplification in standard single-mode fibers," *Opt. Express*, vol. 16, no. 26, pp. 21692-21707, 2008.

[23] R. Waarts, A. Friesem, and Y. Hefetz, "Frequency-modulated to amplitude-modulated signal conversion by a Brillouin-induced phase change in single-mode fibers," *Opt. Lett*. vol. 13, no. 2, pp. 152-154, 1988.

[24] O. Shlomovits, T. Langer, and M. Tur, "The effect of source phase noise on stimulated Brillouin amplification," *J. Lightwave Technol.*, vol. 33, no. 12, pp. 2639-2645, 2015.

[25] C. Wang, Y. Han, F. Pang, L. Chen, and X. Bao, “Polarization dependent Brillouin frequency shift fluctuation induced by low birefringence in single mode fiber,” *Opt. Express*, vol. 25, no. 25, pp. 31896–31905, 2017.

[26] P. Johannisson, M. Sjodin, M. Karlsson, E. Tipsuwannakul and P. Andrekson, “Cancellation of nonlinear phase distortion in self-homodyne coherent systems”, *IEEE Photonic Tech. L.*, vol. 22, no. 11, pp. 802-804, 2010.

[27] R.S. Luís, B.J. Puttnam, J.M.D. Mendinueta, Y. Awaji and N. Wada, “Experimental demonstration of a polarization-insensitive self-homodyne detection receiver for optical access”, in *Proc. European Conference on Optical Communication (ECOC)*, paper Tu.3.4.7, Valencia, 2015.

[28] T. Kan, K. Kasai, M. Yoshida, and M. Nakazawa, “42.3 Tbit/s, 18 Gbaud 64 QAM WDM coherent transmission over 160 km in the C-band using an injection-locked homodyne receiver with a spectral efficiency of 9 bit/s/Hz”, *Opt. Express*, vol. 25, no. 19, pp. 22726-22737, 2017.