# System feasibility of using stimulated Brillouin scattering in self coherent detection schemes

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# System feasibility of using stimulated Brillouin scattering in self coherent detection schemes

**Luca Banchi*, Marco Presi, Roberto Proietti, and Ernesto Ciaramella**

*Scuola Superiore S'Anna, P.zza Martiri della Libertà, 33-56127–Pisa, Italy*
**l.banchi@sssup.it*

**Abstract:** We demonstrate the first self-coherent detection of 10 Gbit/s BPSK signals based on narrow-band amplification of the optical carrier by means of Stimulated Brillouin effect in a common fiber. We found that this technique is very effective only if it is combined with proper line coding and high-pass electrical filtering at the receiver. In this case we obtain OSNR-performance close to the ideal coherent receiver.

**OCIS codes:** (060.4510) Optical communications; (200.4740) Optical processing.

## References and links

1. S. Tsukamoto, D. S. Ly-Gagnon, K. Katoh, and K. Kikuchi, "Coherent Demodulation of 40-Gbit/s Polarization-Multiplexed QPSK Signals with 16-GHz Spacing after 200-km Transmission," in *Proceedings of Optical Fiber Communications Conference*, paper PDP29, San Diego, 2005.
2. C. R. S. Fludger, T. Duthel, D. van den Borne, C. Schulien, E. D. Schmidt, T. Wuth, J. Geyer, E. De Man, G. D. Khoe, and H. de Waardt, "Coherent equalization and POLMUX-RZ-DQPSK for robust 100-GE transmission," IEEE J. Lightwave Technol. **26**(1), 64–72 (2008).
3. T. Miyazaki, and F. Kubota, "PSK self-homodyne detection using a pilot carrier for multibit/symbol transmission with inverse-RZ signal," IEEE Photon. Technol. Lett. **17**(6), 1334–1336 (2005).
4. M. J. Fice, A. J. Seeds, B. J. Pugh, J. M. Heaton, and S. J. Clements, "Homodyne Coherent Receiver with Phase Locking to Orthogonal-Polarisation Pilot Carrier by Optical Injection Phase Lock Loop, " in *Proceedings of Optical Fiber Communications Conference*, paper OTuG1, San Diego, 2009.
5. B. J. C. Schmidt, Z. Zan, L. B. Du, and A. J. Lowery, "120 Gbit/s over 500-km Using Single-Band Polarization-Multiplexed Self-Coherent Optical OFDM," IEEE J. Lightwave Technol. (to be published).
6. J. Arnaud, "Enhancement of optical receiver sensitivities by amplification of the carrier," IEEE J. Quantum Electron. **4**(11), 893–899 (1968).
7. C. G. Atkins, D. Cotter, D. W. Smith, and R. Wyatt, "Application of Brillouin amplification in coherent optical transmission," Electron. Lett. **22**(10), 556–558 (1986).
8. M. Horowitz, A. R. Chraplyvy, R. W. Tkach, and J. L. Zyskind, "Broad-band transmitted intensity noise induced by Stokes and anti-Stokes Brillouin scattering in single-mode fibers," IEEE Photon. Technol. Lett. **9**(1), 124–126 (1997).
9. D. Cotter, D. W. Smith, C. G. Atkins, and R. Wyatt, "Influence of nonlinear dispersion in coherent narrowband amplification by stimulated Brillouin scattering," Electron. Lett. **22**(12), 671–672 (1986).
10. J. Geng, S. Staines, Z. Wang, J. Zong, M. Blake, and S. Jiang, "Highly stable low-noise Brillouin fiber laser with ultranarrow spectral linewidth," IEEE Photon. Technol. Lett. **18**(17), 1813–1815 (2006).
11. G. Ritt, G. Cennini, C. Geckeler, and M. Weitz, "Laser frequency offset locking using a side of filter technique," Appl. Phys. B **79**(3), 363–365 (2004).
12. F. Ronghui, and Y. Peida, "Numerical analisys of Brillouin amplifiers for use in self-homodyne detection," Microw. Opt. Technol. Lett. **4**(9), 361–365 (1991).

## 1. Introduction

Optical coherent systems recently re-gained a lot of attention thanks to Digital Signal Processing (DSP), which promises to solve the polarization and phase locking issues that so far prevented the realization of coherent optical systems. Whilst DSP-based systems were proven to be effective at 40 Gbit/s [1], it is not yet clear if they could be efficiently scaled to higher rates (i.e. 100 Gbit/s) because of the increasing complexity and cost: practical electronic processing must indeed implement a substantial number of complex functions (e.g. recovery of the carrier polarization, frequency and phase, clock recovery and signal equalization [2]). All-optical self-homodyne detection (SHD) is a promising technique that can alleviate the constrains of DSP-enabled receivers. It was demonstrated using a pilot carrier, having a polarization state orthogonal with respect to that of the signal [3]. Self-

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coherent detection can also be obtained using an optical injection-locked DFB laser, which can produce effective phase-locking of the local-oscillator (LO) to the input signal. A system demonstration of this latter scheme was experimentally performed on both 10 Gbit/s ASK and PSK signals [4]. A similar solution may also be used for OFDM signals [5].

In principle, an alternative scheme was proposed many years ago, which is based on the selective amplification of the signal carrier by means of a Brillouin amplifier (BA) [6,7]. Since the BA works as a narrow-band amplifier, it can amplify only the carrier. The amplified carrier works as an ideal LO (perfectly locked in frequency and polarization), thus the photo-detection effectively produces the phase-to-amplitude conversion. This approach only requires to lock the optical frequency of the pump to that of the signal within the BA bandwidth ($\Delta\nu_{BA} \approx 10$ MHz), which is by far easier than the usual phase-locking. However, to the best of our knowledge, no effective system demonstration of this concept was ever presented. This was most likely because the obtained signal is highly affected by spurious intensity noise of the Brillouin amplification, which is known to have a very high noise figure [8].

Here we present the first proof-of-principle system demonstration of the technique, carried out using a 10 Gbit/s BPSK signal. We start from the experimental evidence that the electrical noise due to the BA is very high, but it is concentrated only at low frequencies. This leads us to introduce an *ad hoc* solution, which is based on the combined use of signal coding and electrical filtering. First, a high-pass electrical filter (HPF) is used at the receiver to suppress the spurious noise. Furthermore, in order to prevent inter-symbol interference (ISI), the signal spectral content at low frequency is strongly reduced by proper coding. We found that the interplay of these two elements effectively suppresses the amplification noise, so that performance close to the ideal coherent receiver can be achieved.

## 2. Experimental setup

We realize the 10 Gbit/s BPSK self-coherent receiver using the setup shown in Fig. 1. The adopted external cavity laser (ECL, $\lambda_0 = 1545.329$ nm) has a linewidth of 100 kHz. This value is much lower than the BA gain bandwidth (about 10 MHz), this allows for a stable operation condition, as discussed in [7] and [9]. The ECL output is first modulated by a low-phase noise RF tone at 5.467 GHz by means of Mach-Zehnder intensity modulator (MZM) biased at null. At the MZM output we thus obtain two CW light-waves (Inset a) having a stable frequency separation corresponding to the Brillouin frequency shift $\Delta f_B$ ($\Delta f_B = 10.934$ GHz in our fiber). The lightwave at the shorter wavelength will act as the BA pump. Here we choose this approach just for the sake of simplicity. In a real application, the pump wave should be generated at the receiver and thus frequency-locked to the signal by some other technique. The relative frequency of the pump laser and the signal laser must be locked so that the frequency drift is confined to be within the Brillouin gain bandwidth (about 10 MHz). There are a number of common techniques that can be used to achieve this result [10,11]. Moreover in a real system the pump and the signal have to be co-polarized so polarization tracking would also be required. The pump and the signal waves are separated by means of a Fiber Bragg Grating (FBG), which reflects the signal at $\lambda_S = 1545.373$ nm (Inset b) and transmits the pump at $\lambda_P = 1545.285$ nm. The pump is further filtered to suppress the residual wave at $\lambda_S$ (Inset c) using a flat-top tunable filter (FTTF) with 0.15 nm FWHM and is then amplified by means of an Erbium-doped fiber amplifier (EDFA). After the EDFA, a variable optical attenuator (VOA-1) is used to control the BA gain. The BA is realized by a 25 km-long single mode fiber (SMF, attenuation 0.2 dB/km, 0 dBm stimulated Brillouin scattering threshold). On the signal side, the CW signal reflected by the FBG is extracted by means of an optical circulator (OC-1) and BPSK-modulated by means of a $LiNbO_3$ phase modulator (PM) driven by a 9.952 Gbit/s $2^7$-1 PRBS (Inset d). It is then amplified by an EDFA and passes through VOA-2 to adjust the signal power. In order to change the received optical signal-to-noise ratio (OSNR), we use a noise-loading stage made of two cascaded amplifiers (an EDFA and a semiconductor optical amplifier SOA) and a 0.8 nm optical tuneable filter (OTF). Finally the BPSK signal is injected into the BA, where the carrier amplification takes place.

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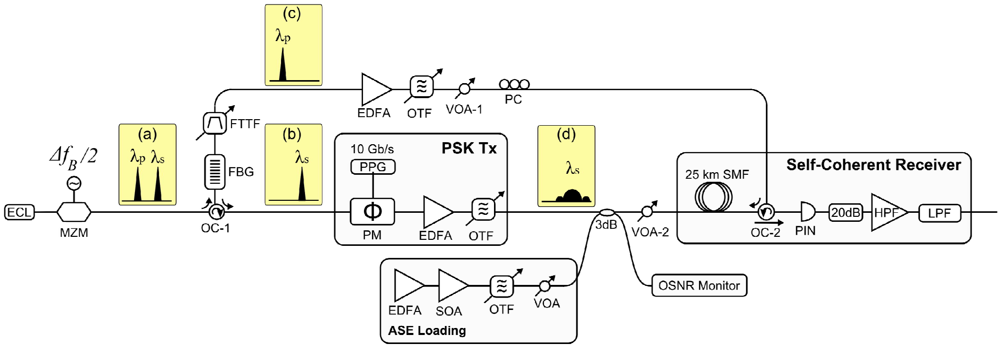

Fig. 1. Experimental Setup. ECL: External Cavity Laser; FBG: Fiber Bragg Grating; MZM Mach-Zehnder Modulator; FTTF: Flat-Top Tunable Filter; OC: Optical Circulator; PPG: Pulse Pattern Generator; PM: Phase Modulator; EDFA: Erbium Doped Fiber Amplifier; SOA: Semiconductor Optical Amplifier; OTF: Optical Tunable Filter; VOA: Variable Optical Attenuator; PC: Polarization Controller; HPF: High-Pass Filter; LPF: Low-Pass Filter. The insets indicate the optical spectra at various points in the setup (a-d).

The pump is injected from the opposite end of the BA by means of OC-2, which also allows to extract the amplified signal. The BA peak gain is about 22 dB and the measured gain bandwidth (at −3 dB) is about 5 MHz. BA saturation occurs at 0 dBm input power. The signal power is adjusted by means of VOA-2 in order to saturate the BA gain, so that the effects of any intensity noise present in the signal carrier and in the BA pump are minimized [12]. The BA output signal is then direct-detected using a 10 GHz bandwidth PIN photodiode (−18 dBm sensitivity). The PIN electrical output is first attenuated by a 20 dB electrical attenuator and then amplified by means of an electrical band-pass amplifier having 5 MHz-8 GHz bandwidth, and 30 dB gain. The amplifier here works as a 5 MHz cut-off HPF. An usual 4th order low-pass Bessel filter (bandwidth = 7.5 GHz) is introduced after the amplifier. A clock and data recovery unit is then used for Bit Error Ratio (BER) measurements. In our experiment we consider as self-coherent receiver the combination of the BA (composed by the 25 km-long SMF and the pump) and the PIN photodiode followed by the electrical amplifier.

## 3. Experimental results

Figure 2 reports the optical spectra of the BPSK signal before and after the carrier selective amplification [Fig. 2(a) and Fig. 2(b) respectively]. In order to stimulate the amplification the input BPSK signal is very slightly under-modulated, so that the carrier at $\lambda_S$ is not completely suppressed (the same result can be achieved by exact modulation and proper coding). In the inset in Fig. 2(a) the eye diagram of the slightly under-modulated BPSK signal before the carrier selective amplification is reported and it shows no significant residual intensity modulation. After the BA, the carrier is effectively amplified by 14 dB [Fig. 2(b)]. The BA gain is experimentally optimized by means of VOA-1 in order to maximize the received eye aperture. As it can be seen, in the amplified signal spectrum a very low secondary peak is present, due to the Rayleigh back-scattered pump; since this falls out-of-band, it has no impact on the receiver performance.

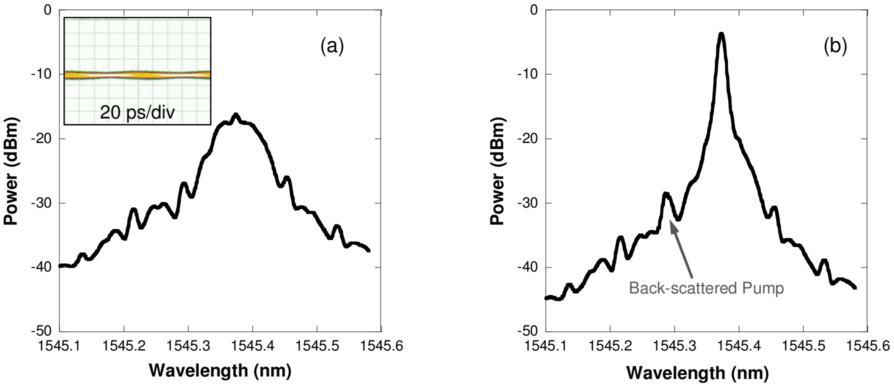

Fig. 2. Optical Spectra of the BPSK signal before (a) and after (b) the carrier selective amplification. Inset: eye diagram taken for the under-modulated BPSK signal before the carrier selective amplification (y-scale: 20 mV/div).

In Fig. 3 we report the eye diagrams of the 9.952 Gbit/s BPSK signal taken with no noise loading. In Fig. 3(a) the eye diagram is obtained by fiber BA with no post detection high-pass filtering: it clearly shows a significant amplification noise.

Since the BA noise is mostly concentrated in the low frequency region, it should be effectively suppressed by introducing a post-detection HPF after the photodiode. This filter however introduces substantial distortions on the usual signal, which has non-negligible low frequency components. Therefore, in order to prevent this ISI, we code the transmitted data using a DC-balanced line code, having suppressed low frequency content. We then use a BPSK signal that is 8B-10B coded, which suppresses the signal spectral components in the frequency range 0 to 5 MHz: this dramatically improves the performance. As an example Fig. 3(b) shows the eye diagram taken for the 8B10B coded 9.952 Gbit/s BPSK signal with the post-detection filter: we see here a much better shape, a wider opening and a reduced residual BA noise compared to Fig. 3(a). In the same figure we also report the eye diagram of a standard 9.952 Gbit/s NRZ-OOK signal received by direct detection [Fig. 3(c)].

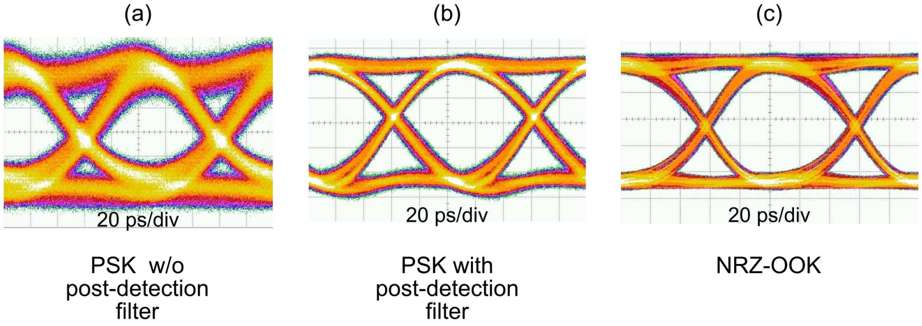

Fig. 3. Eye diagrams of: (a) coherent detected BPSK using only BA, (b) coherent detected BPSK using also post-detection HPF and 8B-10B line coding, and (c) direct detected OOK (y-scale: 50 mV/div).

In Fig. 4 we report the performance of the proposed self-coherent receiver in terms of BER measurements. In our experimental setup the optical ASE noise limits the performance of the receiver. In Fig. 4 the white-circles are obtained for the 9.952 Gbit/s BPSK signal with no post-detection filter: this configuration has more than 8 dB OSNR penalty (at BER = $10^{-9}$) compared to the theoretical limit for the balanced receiver (dashed-line). This huge penalty is due to the noise of the BA. The black-circles report the BER curve for the optimized self-coherent receiver (a proper DC-balanced line coding and the post-detection filter). This shows a very high improvement: this is mostly achieved thanks to the electrical HPF after the photodetection, which effectively suppresses the high noise due to the BA. Finally we thus compare our results to the theoretical limit for BPSK coherent detection with balanced receiver which is also shown in Fig. 4 (dashed-line) We can see about 3 dB OSNR penalty at BER = $10^{-9}$. However our receiver is single-ended, and it is well known that the balanced detection receiver outperforms it by around 3 dB. Therefore we can estimate that our receiver is close to the limit for single-ended coherent detection of optical BPSK. This demonstrates the effectiveness of the post-detection HPF when combined with a proper line code to increase the system performance. For completeness, we also report in Fig. 4 the performance of a standard 9.952 Gbit/s NRZ-OOK signal received by direct detection (squares). As expected, the eye diagram of the OOK signal [Fig. 3(c)] has a good quality, but we observe an OSNR penalty of about 3 dB in respect to the BPSK received using self-coherent receiver with the HPF filter.

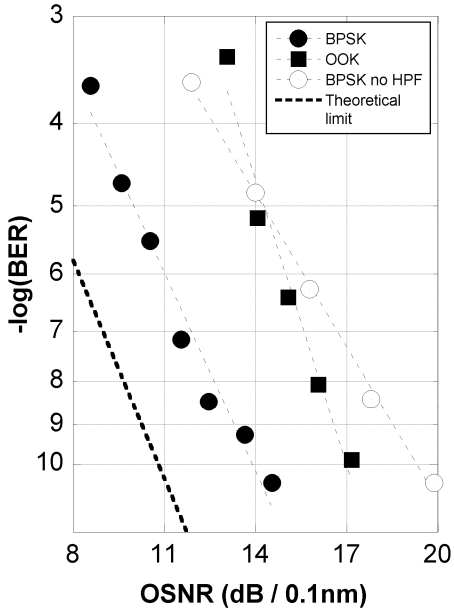

Fig. 4. BER curves for the coherent detected BPSK with HPF (black-circles) and without (white-circles). Curves of the IM-DD (squares) and the theoretical limit for BPSK coherent detection with balance receiver (dashed line) are also plotted for comparison.

## 4. Conclusions

We have presented the first proof-of-principle system demonstration that a self-coherent receiver can be effectively realized by using the selective amplification of the carrier by stimulated Brillouin effect. We found that the most limiting effect is the low-frequency intensity noise produced by the SBS: we thus demonstrated that it can be made ineffective by means of the combination of a high-pass electrical filter and of a DC-balanced line-coding (8B10B).

We tested the technique on a 10 Gbit/s BPSK signal, which was received with BER performance quite close to the ideal BPSK coherent receiver. In order to prove our concept, we made a number of simplifying assumptions. First, we used a pump source that is intrinsically stable, whose frequency is already optimized. In a realistic application this should be replaced by a laser whose frequency is dynamically controlled by means of a simple electrical feedback: since the control should be at low frequency and should aim at maximizing the received power we believe that this would not pose a critical challenge to

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system implementations. Additionally, in our demonstration we used a common SMF as the Brillouin medium, which was 25-km long: for practical implementations, this may be replaced by a more compact and shorter highly nonlinear fiber.

Finally here we demonstrated our concept on a 10 Gbit/s BPSK signal, but it can be expected the use of effective self-coherent detection can be further extended to higher bit rates and, likely, to different modulation formats. In all these cases, it might help to reduce the complexity of DSP-based detection schemes.

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