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Record-sensitivity receiver at 1 photon/bit for free-space applications

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Abstract: We demonstrate 1 photon-per-bit receiver sensitivity at 10.52 Gb/s enabled by a low-noise phase-sensitive pre-amplifier in combination with injection-locking-based pump recovery operating at sub nano-Watt powers

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1. Introduction

In long-haul free-space optical communication links where diffraction is the main cause of link loss, the available reach and data throughput is primarily dictated by the available transmission power, the aperture size, and the receiver sensitivity. Therefore advances in receiver sensitivity technology lead to a direct reach extension and there is thus a large interest in solutions that can provide the best possible practical receiver sensitivity, quantified in photons-per-bit (PPB). Spectral efficiency on the other hand is only of importance in regards to achieving a desired bit-rate through a limited receiver bandwidth, as systems are typically single channel. Often pulse-position modulation (PPM) is employed in a sensitivity vs. bandwidth trade-off [1]. Photon-counting receivers used at very low signal-to-noise-ratio (SNR) are bound by a higher capacity than coherent detection [2]. However, while practical receivers operating in the 1550 nm wavelength range have shown great promise, they tend to have limited bandwidth, restricting the maximum bit rate and are suffering from low detection efficiencies. Approximately 0.5 PPB sensitivity was reported at 781 Mb/s using 32-ary pulse-position modulation (PPM) and a half-rate forward-error correction (FEC) code [3] and at 187 Mb/s with 64-ary PPM [4]. However, the low detection efficiency (3% [3]) and high insertion loss (11 dB [4]) resulted in sensitivities with respect to incident photons being more than a factor of 10 higher. Over the last decade attention has shifted to advanced modulation formats and coherent detection in combination with advanced FEC to push both data-rates and detector sensitivity as homodyne detectors offers the highest sensitivity of traditional non-photon-counting detectors.

The capacity of the shot-noise homodyne detector was derived by Gordon in [2] as:

$$C_{homodyne} = \frac{B}{2}\log_2\left(1+\frac{4\varepsilon S}{h\nu B}\right)$$

where B is the bandwidth of the signal, S is the signal power, is the quantum efficiency of the detector, h is Plancks constant, and ν the optical frequency. The ultimate sensitivity is thus provided by homodyne detection with unity quantum efficiency. In [5] pure homodyne detection of a BPSK signal was been demonstrated with excellent performance; 1.5 PPB at 156 Mb/s using a half-rate code. Another approach is to use an optical preamplifier to improve the sensitivity with several impressive demonstrations summarized in figure 1(a) The sensitivity in this case is limited by the noise-figure (NF) of the pre-amplifier (expressed by an effective $\varepsilon = \frac{1}{NF}$ in equation (1)) which is fundamentally at least 3-dB for traditional amplifiers. The NF of a phase-sensitive optical amplifiers (PSA) on the other hand can be 0 dB in theory [6] and has been demonstrated as low as 1 dB [7]. So far, PSAs have been primarily used for improving fiber communication systems [8], however, as near-noiseless preamplifiers in optical receivers, they have the potential to provide the ultimate sensitivity in long-haul free-space links. We recently demonstrated a record sensitivity of 1 photon-per-information-bit using a PSA pre-amplified receiver at a rate of 10.52 Gb/s [10], representing a significant improvement at similar data rates [9]. The system uses QPSK modulation with standard blind digitial signal processing and a regular half-rate FEC code. While the PSA requires co-transmission of pump and idler waves with the signal, the combined power of all three waves was below 1 PPB, largely enabled by injection locking based pump recovery resulting in a nearly negligible penalty due to its presence.

2. Experimental setup

Figure 1(a) shows the experimental setup of the transmitter and PSA pre-amplified receiver. The transmitter consisted of an external cavity laser (ECL) signal laser (linewidth 50 kHz) at 1550.65 nm, modulated using an IQ modulator to generate 10.52 Gbaud QPSK. The data was generated with a pattern generator programmed with

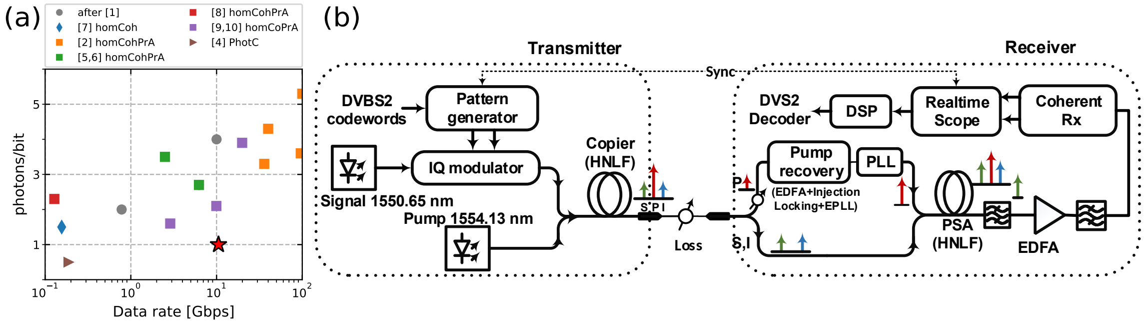

Fig. 1. Right: Experimental setup. Left: Previous sensitivity records, homCoh: coherent homodyne detection, homCohPrA: coherent homodyne detection with pre-amplification (EDFA), PhotC: Photon Counting detector, (*) 11 dB unaccounted conversion loss, () detected photons with 3% detection efficiency. Our result is denoted by the star.

FEC encoded data using a digital video broadcasting standard (DVB-S2) code, consisting of a concatenation of a -rate soft-decision LDPC code and an outer high-rate (0.6%) BCH code. The length of each code word was 64,800 bits with 10 code words in each measurement batch. I and Q channels were modulated with the same coded bit pattern delayed by 19 bits. The modulated signal was then combined with the a fiber laser at 1554.13 nm (linewidth 100 Hz) as a pump to generate a conjugated idler at 1557.6 nm containing the same data as in the signal via four-wave mixing (FWM) in a highly nonlinear fiber (HNLF). The loss in a free-space channel was emulated with a variable attenuator. For a practical power limited system the total power of pump, signal and idler is the limiting factor. We therefore transmit a pump with significantly lower power than the combined signal and idler power. For practical reasons, instead of at the transmitter, we attenuated the pump at the receiver stage, but this should have no implications for our conclusions. The fact the we transmit three waves vs. conventionally one, is not essential from a power budget point-of-view as a saturated booster amplifier will provide the same total output power in both cases. At the receiver, the pump was separated from the signal-idler path for regeneration, using a WDM coupler (0.5 dB). For the recovery of the very weak pump we used an EDFA pre-amplified injection-locking (IL) scheme with an electrical PLL, capable of recovering a stable pump at input powers as low as -71 dBm which was 12 dB below the lowest used signal plus idler power for error-free operation (-59 dBm) resulting in a penalty of only 0.26 dB [16]. The received signal and idler were then combined with the regenerated pump in a second WDM coupler (0.5 dB) for phase sensitive amplification in a cascade of HNLFs providing 21 dB of gain. An optical PLL after the pump recovery was used to maintain the relative phase between pump, signal and idler for maximum phase-sensitive gain. The OSNR of the signal was measured using an optical spectrum analyzer (OSA) and used to calculate a PSA NF of 1.2 dB. Importantly, the received power used for sensitivity calculation was the total combined signal, idler and pump powers, where the signal and idler powers were measured just before PSA stage, at point A in the figure whereas the pump is measured just before the regenerator, at point B in the figure. The amplified and filtered signal was then passed through an EDFA (G 25 dB) to provide sufficient power for the receiver, without influencing the NF significantly. The signal was filtered out (idler not being used) and measured in a coherent receiver with a free-running local oscillator (LO) laser (ECL 20 kHz) operating close to the signal wavelength. The signal was digitized with a real-time oscilloscope at 50 GS/s over a 7 sec time duration capturing all 10 code words. The data was processed offline with a regular digital signal processing chain consisting of IQ-imbalance compensation, frequency offset estimation, CMA equalization (7 taps) and phase estimation using QAMpy [17], without data-aided pre-convergence, before FEC decoding.

3. Results

Figure 2(a) shows the measured performance in terms of generalized mutual information (GMI) averaged over 10 batches of ¿700 000 symbols each. As a guide we have included a curve corresponding to 1 bit/photon as well as the theoretical curves for a shot-noise limited homodyne detector, a heterodyne receiver or pre-amplified phase-insensitive amplifier with a minimum noise figure of 3-dB, as well as a curve for our PSA calculated from the measured OSNR corresponding to a 1.2 dB PSA NF. We can clearly see that five of our measurement results are above the 1 bit/photon limit thus potentially achieving a 1 PPB sensitivity with a theoretical FEC code. The light and dark shaded areas indicate the regions where a sensitivity of ¡ 1 PPB is theoretically possible, given a perfect homodyne detector without amplification (or preamplified with a 0-dB NF amplifier) and with a 3-dB noise figure amplifier, respectively. The very small dark shaded region highlights the difficulty in achieving a 1 PPB sensitivity at Gb/s rates using a traditional pre-amplifier.

To fully confirm the performance of our system we decoded the DVBS2 coded bits. The average pre-FEC bit-error-rates (BERs) and the post-FEC BERs of the individual batches (10 at each power level) are shown in

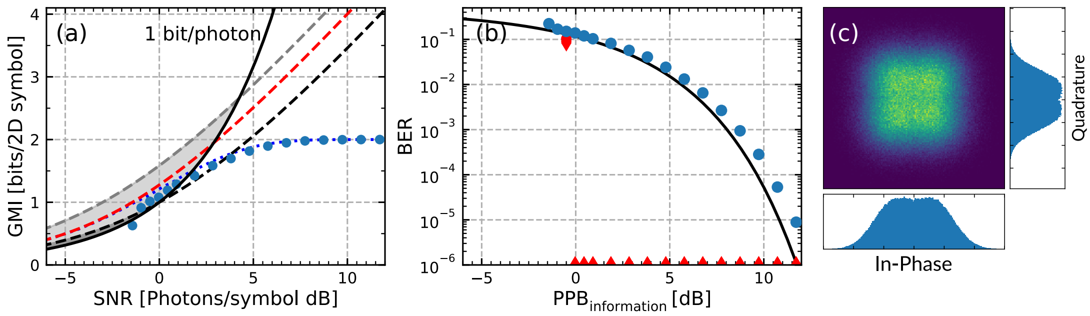

Fig. 2. Experimental results (a) in terms of Generalized Mutual Information (GMI), gray-dashed: capacity for unamplified coherent homodyne receiver, black-dashed: capacity for heterodyne or homodyne receiver with pre-amp (NF: 3 dB), red-dashed: capacity for homodyne with PSA pre-amp (NF: 1.2 dB), blue-dashed: GMI theory (b) pre- (blue) and post-FEC (red) BER vs photons per information bit (assuming rate code), (black) theory based on measured OSNR (c) constellation diagram at 1 PPB resulting in error-free decoding. Note that the x-axis in a) and b) includes all the photons in signal, idler, and pump combined.

figure 2(b). We can see that all batches are decoded to error free above -0.03 dB photons per symbol confirming that our receiver operates at a sensitivity of 0.99 PPB (taking into account the FEC overhead). For lower powers decoding did not result in a significant BER reduction and we omitted decoding at the lowest SNRs. We note that at all power levels, we observed instabilities, which resulted in failure to achieve DSP convergence. We attribute this to small back-reflections causing injection locking instabilities, which caused phase-noise bursts. We thus discarded a small number of batches. We believe this could be avoided improving isolation of the injection locking process. An example constellation diagram at 1 PPB with error-free recovery is shown in figure 2(c).

4. Discussion and conclusions

The approach shown here is compatible with other methods for further sensitivity improvements, e.g. power-efficient modulation formats, spatial/spectral diversity, and advanced soft-decision FEC, and is furthermore straightforwardly scalable to higher bit rates. It should be noted that transmitting both signal and idler results in a reduction of the spectral efficiency (SE), the PSA therefore constitutes a similar SE to SNR trade-off as PPM formats. However, because it is not necessary to detect the idler, there is no requirement to increase the bandwidth of the electrical components, unlike PPM which implies higher bandwidth electronics if one wants to improve sensitivity while keeping the bitrate constant. Moreover, the ability for noise-less amplification is unique to the PSA, circumventing the limited quantum efficiency of coherent receivers. In our experiment, the black-box receiver sensitivity was 1 dB higher due to the two relatively lossy WDM couplers, i.e. 1.2 PPB (1.0 PPB based on GMI), albeit this is not a fundamental limit. In summary, we have demonstrated an optical receiver with a sensitivity of 1 PPB (decoded) or 0.8 PPB (GMI-based) at a 10.52 Gb/s data rate (excluding the mentioned WDM losses) which, to the best of our knowledge the lowest sensitivity achieved at Gb/s rates. Our results demonstrate the fundamental advantage of PSAs in free-space receivers allowing an extension of reach, increase of information transmission rate, and/or reduction of the size of the involved optics.

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References

1. D.O. Caplan, in Free-Space Laser Communications **2** (2007)
2. J. P. Gordon, Proceedings of the IRE **50**, 1898–1908 (1962).
3. B.S. Robinson et al., Opt. Lett **31**, 444–446 (2006).
4. M.E. Grein et al. in CLEO 2008
5. M.L. Stevens et al. Opt. Express **16**, 10412–10420 (2008)
6. C. M.Caves, Phys.Rev.D **26**, 1817–1839 (1982)
7. Tong, et al. Nat. Phot. **5**, 430 (2011).
8. S. Olsson et al., Nat. Comms **9**, 2513 (2018)
9. D. J. Geisler et al., OFC 2013
10. R. Kakarla et al. in CLEO 2019 PDP
11. D. J. Geisler et al. Opt. Eng **55**, 111605 (2016)
12. D. Lavery et al., in OFC 2012
13. X. Liu at al, in ECOC 2011
14. X. Liu, et al. in OFC 2011, PDPB1
15. Ludwig et al., Opt. Express **23** 21942-21957 (2015)
16. R. Kakarla et al.. Opt. Lett. **43**, 5769–5772 (2018)
17. J. Schröder and M. Mazur, DOI: 10.5281/zenodo.119