Demonstration of Automatically Phase-Locked Self-Homodyne Detection with a Low-Power Pilot Tone based on Brillouin Amplification and Optical Frequency Combs

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Abstract: A scheme of automatically phase-locked self-homodyne detection with a low-power pilot-tone is proposed. The performance is experimentally demonstrated by back-to-back 10/20-Gbaud BPSK, 10-Gbaud QPSK and 100km-transmission of 10-Gbaud BPSK with pilot-to-signal power ratio of -30dB.

OCIS codes: (060.2920) Homodyning; (060.2360) Fiber optics links and subsystems

1. Introduction

Coherent optical detection systems form an important part of advanced modern-day telecommunications deployment [1,2]. An important aspect of coherent optical detection systems is that the required local oscillator (LO), which beats with the incoming signal, should be phase and frequency locked through optical or electrical approaches [3-5].

Self-homodyne detection (SHD) system typically sends a pilot tone together with the data signal at the transmitter side. In the receiver, the pilot tone is retrieved and used as a LO through different approaches [6-11]. The SHD system has the potential to reduce the receiver complexity and relax the requirement of laser linewidth.

In general, a high-power pilot tone is favorable for the phase locking of SHD. However, it degrades the OSNR of the data channel given a constant total transmitter power [6,8]. To overcome the power ratio trade-off, a laudable goal might be to have a low-power pilot tone at the transmitter but a high enough pilot tone power at the receiver in order to have efficient SHD performance.

In this paper, we experimentally demonstrate an automatically phase-locked SHD system with a low-power pilot tone adjacent to the data channel. Our scheme includes two stages: First, only the pilot tone is amplified by Brillouin amplification (BA) [12]. Second, the amplified pilot tone is moved into the middle of the data channel by a comb-based phase preserving wavelength conversion. By tuning the relative phase between the comb lines, both in-phase (I) and quadrature (Q) components of the data channel can be directly detected without post signal processing. With the pilot-to-signal power ratio (PSR) of -30dB, the proposed SHD system is experimentally demonstrated on back-to-back (B2B) 10/20 Gbaud BPSK and 10 Gbaud QPSK systems. A 100km transmission of 10 Gbaud BPSK with the proposed SHD system is also tested.

2. Concept

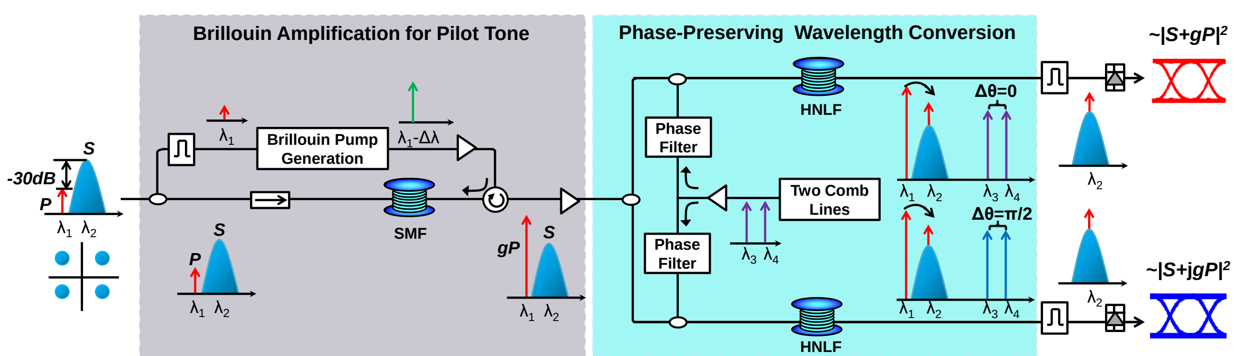

Fig. 1. Concept of the proposed automatically phase-locked self-homodyne detection (SHD) with a low-power pilot tone. It includes two stages: 1) Brillouin amplification for pilot tone; 2) phase-preserving wavelength conversion based on a pair of coherent comb lines.

Figure 1 shows the concept of the proposed automatically phase-locked SHD with a low-power pilot tone. The input signal includes a data channel (*S*) and a pilot tone (*P*) with a low PSR (-30dB). In the first stage, a small portion of the pilot tone is extracted to generate Brillouin pump with a wavelength (frequency) shift of Δλ. After amplified by an erbium-doped fiber amplifier (EDFA), the Brillouin pump is injected into a single-mode-fiber (SMF) with the direction opposite to that of the input signal (*S* and *P*). Here, only the pilot tone is amplified by a gain coefficient *g* since BA works as a narrowband amplifier. It is noted that except for a small portion of the pilot tone, which is extracted for Brillouin pump generation, the most part of it is kept with the data channel (*S*) in the same path as shown in Fig. 1.

In the second stage, the data channel (*S*) and the amplified pilot tone (*gP*) are coupled with a pair of coherent comb lines. The frequency offset between the two comb lines equals to the one between the data channel and the pilot tone. Then, all the components are injected into two separate highly nonlinear fibers (HNLFs), where the pilot tone is moved to the middle of the data channel by nonlinear four-wave-mixing (FWM). Both in-phase (I) and quadrature (Q) components of the data channel can be selected by adjusting the relative phase (Δθ) between the two comb lines based on separate optical programmable phase filters. After the optical filter and the photodiode (PD), both I and Q components of data channel (*S*) can be directly detected as shown in Fig.1.

3. Experimental Setup

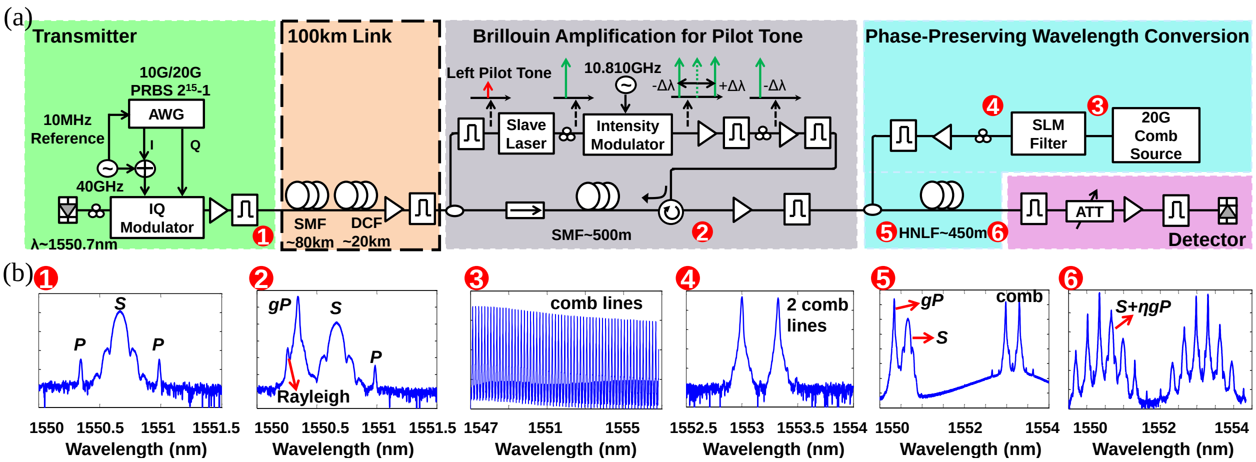

Fig. 2. (a) Experimental setup for the proposed self-homodyne system with PSR of -30dB; (b) measured spectra at the corresponding nodes

Figure 2(a) illustrates the experimental setup for the proposed SHD system. 10/20 Gbaud complex signal is generated by a high-speed arbitrary waveform generator (AWG). The in-phase (I) component is then combined with a low-power sinusoidal pilot tone, which is generated by a 40 GHz frequency oscillator. The clocks of the frequency oscillator and AWG are synchronized by a 10 MHz reference. The signal modulates a laser with the wavelength of 1550.7nm. The optical spectrum of the signal after the transmitter is shown in Fig. 2(b1), where the measured PSR is -30dB. Then, the signal goes either to a 100km-transmission (80km SMF + 20km dispersion-compensated-fiber) or directly to the proposed SHD for the B2B system evaluation.

In the SHD, the signal is first sent to two paths. The upper path is for the BA pump generation as in Fig. 2(a). The detailed process is as follows: a narrowband optical filter extracts the left pilot tone, which is sent to a slave laser whose output frequency matches the input pilot tone. Then, the output is modulated by a 10.810 GHz sinusoidal tone with a Mach-Zehnder intensity modulator (MZM) biased at null point. Therefore, the two output continuous waveforms (CWs) are shifted by ±10.810 GHz respectively (Brillouin frequency shift in our SMF). The CW with the shorter wavelength is used as the BA pump, which is selected and amplified by an EDFA with 150mW. BA is realized by the bidirectional propagation between the pump and the original input signal in the 500m SMF. The output signal spectrum is shown in Fig. 2(b2). Since BA is a narrowband amplifier, only the left pilot tone is amplified by 40dB. It is noted that Rayleigh back-scattering generates a low peak in the spectrum of Fig. 2(b2). The signal after BA is then sent to another EDFA with 186mW and a narrowband optical filter, where the Rayleigh back-scattering component is effectively suppressed.

In the next stage, a phase preserving wavelength conversion scheme is realized based on a pair of coherent comb lines and an HNLF. The two comb lines come from a comb source with a 20 GHz repetition rate generated by a mode-locked laser as in Fig. 2(b3). The broad-spectrum comb is sent to a spatial light modulator (SLM) filter for both filtering and phase adjustment. Fig. 2(b4) shows the output two comb lines. After an EDFA with 300mW, the two comb lines are coupled with the signal in a 450m HNLF. The signal spectra before and after the HNLF are shown in Fig. 2(b5,b6). It can be seen after wavelength conversion, the pilot tone is moved to the middle of the spectrum of the data channel. Finally, the data channel with the pilot tone is selected and sent to a high-speed PD for real-time eye-diagram capture and bit-error-rate (BER) measurement.

4. Results and Discussions

The system performance is assessed by implementing the proposed self-homodyne scheme on 10/20 Gbaud BPSK and 10 Gbaud QPSK systems with the PSR of -30dB. For comparison, a 10 Gbaud BPSK system with the residual carrier is generated at the transmitter side and sent directly to the PD. The ratio of the residual carrier is optimized to produce the biggest open eye on the real-time scope. Fig. 3 shows the eye-diagrams for the 10 Gbaud system under different scenarios. Since the pilot tone is kept with the data channel in the same path throughout the system, they are automatically phase locked which generates open eye-diagrams as in Fig. 3. Compared with the case of the BPSK with residual carrier, the quality of the eye-diagram with the proposed SHD is almost preserved. After a 100km transmission, the eye-diagram is degraded, which might be attributed to the residual chromatic dispersion. For QPSK, by changing the relative phase between the pair of coherent comb lines in Fig. 2(b5), both I and Q components can be obtained and the corresponding eye-diagrams are also shown in Fig. 3.

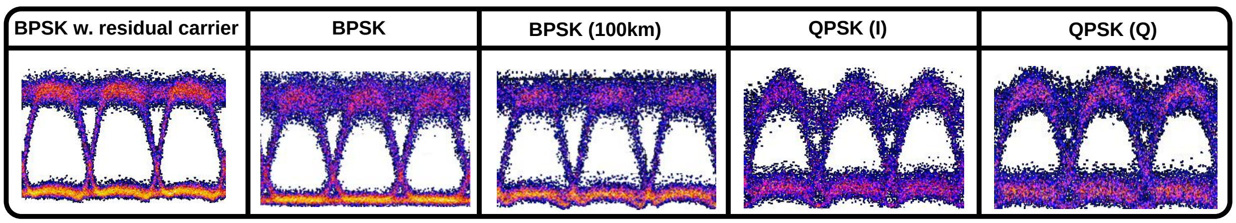

Fig. 3. Comparison of eye-diagrams for 10 Gbaud systems

Figure 4(a) shows the BER measurement for the 10-Gbaud system. For B2B scenario of BPSK, the proposed self-homodyne scheme gives a close performance compared to the BPSK with residual carrier. After a 100km transmission, there is less than 1dB power penalty when BER=1e-3. For B2B scenario of QPSK, compared with BPSK, there is about 4dB power penalty when BER=1e-3. Fig. 4(b) shows the BER for a 20 Gbaud BPSK system. Compared to the BPSK with residual carrier, there is about 0.5dB power penalty when BER=1e-3.

Figure 4(c) shows the measured BER and required Brillouin pump power by changing the PSR at the transmitter while fixing the received power at -8.4dBm. As PSR decreases, the Brillouin pump grows in order to maintain the same received power. Although a dramatic increase of BER is observed when the PSR deceases to -45 dB, which is due to the malfunction of slave laser locking at the extremely low-power input pilot tone, the BER keeps fairly stable for the PSR ranging from -20 dB to -40dB.

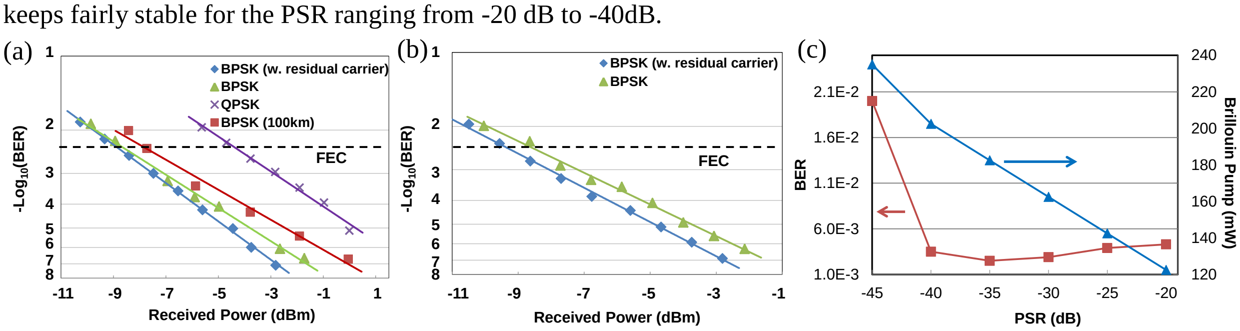

Fig. 4. Real-time BER measurements (a) BER vs. received power for the10 Gbaud BPSK and QPSK systems; (b) BER vs. received power for the 20 Gbaud BPSK system; (c) BER for different levels of PSR and the corresponding powers of Brillouin pump for a fixed received power.

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