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# Phase Regeneration of QPSK Signals Based on Kerr Soliton Combs

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**Abstract:** We demonstrate a phase-sensitive and amplification-based all-optical phase regenerator by utilizing on-chip Kerr soliton combs. In the experiment, we demonstrate the direct generation of a Kerr soliton comb in a silicon nitride micro-ring at the receiver side of optical communication systems by applying the transmitted signal as a pump light. The mutual coherence between the signal and the regenerated Kerr comb is excellent, and the all-optical phase regeneration of a 20 GBaud/s QPSK signal is achieved. In contrast to the traditional scheme, our solution shows better SWaP (size, weight, and power) factors. Our study will enhance the relay and reception performance of all-optical communication systems.

**Keywords:** phase regeneration; Kerr soliton combs; all-optical communication system



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## 1. Introduction

The rapid growth of data traffic on the Internet and in data centers has resulted in an increased burden on optical network nodes in terms of system power consumption due to photoelectric conversion processes. To address this concern, all-optical signal processing systems have been designed, which operate within the optical domain to process optical information. This approach capitalizes on the advantages of photonics, including high-speed transmission, broadband capacity, low power consumption, and a low cost, to significantly enhance the overall performance of communication networks while concurrently reducing energy consumption and operating costs [1,2]. All-optical phase regeneration, as a subcategory of the all-optical signal processing process, offers great advantages in lowering the optical communication system size, weight, and power consumption and the overall cost. This technique primarily employs the phase-sensitive amplification process, which exploits its sensitivity to phase matching to achieve phase noise compression.

In recent years, there has been significant progress in phase-sensitive amplification (PSA) techniques for telecommunications and high-speed signal processing applications. The two primary focus areas are low-noise PSA [3,4] and phase regeneration in high-order modulation formats. Achieving phase regeneration in high-order modulation formats requires solving two major issues: the selection of nonlinear materials and the frequency matching condition between the signal and the pump. The most commonly used non-linear materials for PSA are silicon-based waveguides, highly non-linear fibers (HNLF), and periodically poled $LiNbO_3$ (PPLN) [5–9]. In recent years, there has been increasing interest in the utilization of silicon-based waveguides in photonic and electronic integrated circuits due to their high nonlinear coefficient. At telecommunication wavelengths, however, two-photon absorption (TPA) strongly restricts the transmitted pulse energy in the silicon-based waveguides as it leads to the accumulation of free carriers (FC), resulting in high loss [10–12]. To address this issue, a frequently employed approach involves integrating other non-linear materials to facilitate the PSA process [9]. On the other hand, although HNLFs can achieve phase regeneration without the help of other high nonlinear materials [13], it is common to encounter interference from stimulated Brillouin scattering (SBS), which restricts the incident pulse intensity that can cross paths with them [7,8]. This interference has two manifestations: (1) if the pump power required by the phase-sensitive regeneration process is much higher than the SBS threshold, the SBS process will hinder the actual gain of the phase-sensitive amplification process, and (2) if the pump power required for the phase-sensitive regeneration process is near the SBS threshold, then the SBS process will introduce large amplitude noise in the phase-sensitive regeneration. A common solution is to spool the fiber with a linear strain gradient during the preparation of HNLFs [14], thereby increasing the SBS threshold and achieving phase-sensitive regeneration. Our proposed approach aims to promote the frequency coherence between the signal and the pump using Kerr soliton combs, which enable a phase-sensitive regeneration process in HNLFs at a lower pump input power, avoiding interference from SBS.

Kerr soliton combs have advantages in high-frequency coherence and broad spectrum coverage [15], which satisfy the frequency-matching requirements for phase regeneration in high-order modulation formats. Conventional schemes for generating matching pump lights, such as optical modulation or four-wave mixing (FWM), are often complex and limited by the numbers of the generated comb lines [13,16], as shown in Figure 1a. To address this challenge, we propose a novel carrier recovery scheme to generate Kerr soliton combs. This scheme utilizes a data signal as a pump light to generate Kerr soliton combs in a high-Q microcavity at the receiver side, which can provide hundreds of optical frequency lines characterized by excellent frequency coherence and equally spaced frequencies [15,17,18]. This scheme can meet the needs of future multi-channel, high-capacity, all-optical communication systems and enable multi-channel, high-speed, high-order modulation format signal phase regeneration processes.

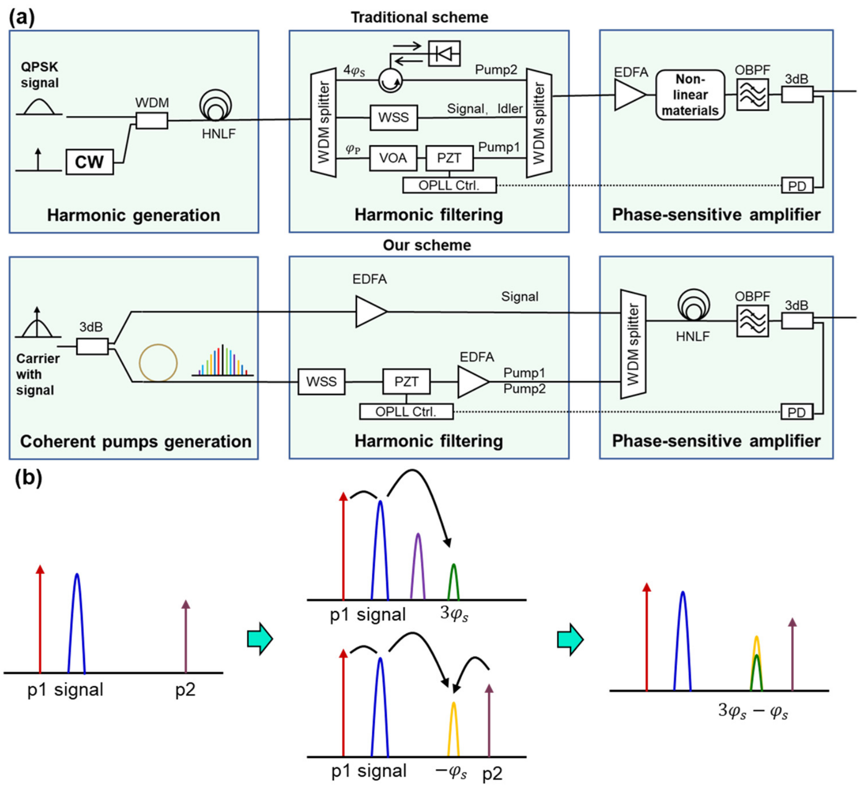


**Figure 1.** (**a**) Comparison between traditional scheme and ours; (**b**) the principle of single-step phase-sensitive regeneration of QPSK. CW: Continuous wave laser; WDM: wavelength-division multiplexer; HNLF: highly non-linear fibers; WSS: wavelength selective switch; VOA: variable optical attenuator; PZT: piezoelectric transducer; OPLL: optical phase-locked loop; OBPF: 0.8 nm optical bandpass filter; 3 dB: 3 dB splitter; EDFA: erbium-doped fiber amplifier; PD: photodetector.

Compared with the traditional scheme for all-optical phase regeneration (as shown in Figure 1a), our scheme can be achieved by using a compact silicon nitride chip with dimensions of $0.5 \times 0.5$ cm$^2$. Furthermore, our scheme can eliminate the operation of self-injection locking for the FWM-based pump2 in the experiment. Therefore, our scheme shows better SWaP (size, weight, and power) factors than the traditional scheme.

In this article, we demonstrate the all-optical phase-sensitive regeneration of a QPSK signal in an HNLF by utilizing Kerr soliton combs generated by a carrier recovery scheme. Our experimental results indicate that the high phase coherence and frequency coherence of the Kerr soliton combs effectively facilitate the phase-sensitive regeneration of a 20 Gbaud/s QPSK signal in HNLFs, without the necessity for linear strain. Furthermore, the impact of different optical carrier-to-signal ratios (OCSR) of a data signal on the performance of a Kerr soliton comb and the subsequent phase-sensitive regeneration is experimentally studied.

## 2. Materials and Methods

Figure 1b shows the fundamental principle of single-step phase-sensitive regeneration of QPSK [19]. HNLFs receive three beams of light, which include a signal and two pumps, referred to as $P_1$ and $P_2$. The phase information carried by the signal is denoted as $\varphi_s$, and the frequency difference between the signal and $P_1$ and $P_2$ is established as $\Delta f_1$ and $\Delta f_2$, respectively. To accomplish the regeneration requirements, $\Delta f_2$ is configured to be thrice that of $\Delta f_1$. The regeneration signal is directly obtained between the signal and $P_2$ during the single-step regeneration process, which is located at a frequency of $\Delta f_1$ away from $P_2$. In order to demonstrate the principle, the details of three light beams undergoing four-wave mixing processes simultaneously in a highly nonlinear fiber (HNLF) are presented in Figure 1b. One of these processes, occurring between $P_1$ and the signal, yields multiple harmonics, including the third harmonic that carries three times the signal phase $3\varphi_s$. The other process, taking place between the signal and the two pumps, results in an idle light that carries the negative signal phase of $-\varphi_s$ at the location of the third harmonic generated in the aforementioned process. According to the principle of phase regeneration, defined in Equation (1), the regenerated case can be obtained by ensuring that the ratio between $-\varphi_s$ idler and $3\varphi_s$ idler equals $1/3(-4.77$ dB). The 4.77 dB reduction in the $3\varphi_s$ idler, as compared to $-\varphi_s$ idler, can be achieved by the adjustment of input power for the three beams. During the digital signal processor, the regenerated QPSK signal $\phi_{s'} = \varphi_s$ can be obtained.

$$A_s(\phi) \cdot \exp(i\phi_{s'}) = \exp(i\phi_s) + \frac{1}{3}\exp(-i3\phi_s), \quad (1)$$

To simplify the intricacy of the conventional system, we employ the Kerr soliton combs to achieve QPSK regeneration. Figure 1a displays our proposed regeneration scheme and the traditional regeneration scheme, both of which consist of three primary components: harmonic generation or coherent pump generation, harmonic filtering, and phase-sensitive amplification. The initial two stages differentiate the two approaches. Specifically, our method utilizes Kerr soliton combs as regenerated pumps, while the conventional method typically employs the FWM process between $P_1$ and the signal to generate two pumps that match the signal frequency. This process passes the signal through a high nonlinear material, resulting in an idle light ($I_1$) carrying three times the signal phase $3\varphi_s$, as well as another idle light beam at $P_2$ carrying four times the signal phase $4\varphi_s$. To achieve phase regeneration, $P_2$ necessitates injection locking to produce continuous light without the signal phase, which negates the impact of the idle light beam carrying four times the signal phase $4\varphi_s$ on $P_2$. Simultaneous feeding of $P_2$, signal, $I_1$, and $P_1$ into the phase regeneration material enables the generation of the idle light ($I_2$) carrying negative three times the signal phase, $-3\varphi_s$, via the FWM process of $P_2$, $I_1$, and $P_1$ at the signal. The superimposition of $I_2$ and the signal produces a regenerative signal carrying the signal phase of $\varphi_{s'}$. A notable drawback of this scheme includes the cumbersome injection locking process and the reliance on the fourth harmonic to generate $P_2$. It requires a sufficiently large conversion efficiency of the high nonlinear material in the first step and necessitates high $P_1$ and $P_2$

power in the regeneration process to produce $I_2$ that satisfies the regeneration requirements. Additionally, using $-3\varphi_s$ idler generated by FWM at the signal in the regeneration process demands a power difference of 4.77 dB between $-3\varphi_s$ idler($I_2$) and the signal, which is problematic because $3\varphi_s$ idler($I_1$) itself is often much smaller than the signal due to being the third harmonic of FWM. In addition, the frequency drift between $-3\varphi_s$ idler($I_2$) and the signal cannot be effectively synchronized by dividing $3\varphi_s$ idler($I_1$) and the signal into two optical amplifications; thus, the use of high power of $P_1$ and $P_2$ in the regeneration process is necessary. The Kerr soliton combs utilized in this study are devoid of the drawbacks noted above. The combs were produced using the auxiliary laser heating (ALH) method [20] on a silicon nitride chip, in which the pumps were derived from carrier recovery. The Kerr soliton combs exhibit uniform frequency spacing and high frequency coherence and can directly generate $P_1$ and $P_2$ without carrying the signal phase. This eliminates the need for injection locking and simplifies the experimentation process by ensuring that the frequency interval requirements between $P_1$, $P_2$, and the signal are met. The principle of single-step QPSK signal regeneration can be utilized to obtain the regenerated signal at the third harmonic frequency produced by $P_1$ and the signal. This regeneration signal is generated by the coherent addition of two FWM processes, and, even at low input power of the pump, the regenerated case can occur when the two idlers ($3\varphi_s$ and $\varphi_s$) satisfy the power relationship. The use of lower input power of the pump can prevent the SBS effect in HNLFs, reduce the interference of amplitude noise in the phase regeneration process, and facilitate phase-sensitive regeneration.

The phase regeneration of the QPSK signal was successfully achieved based on the previously mentioned scheme, as illustrated in Figure 2. A continuous wave (CW) laser with a wavelength of 1550 nm was split into two parts using a 3 dB splitter. One output of the splitter was modulated by 8 or 20 GBaud/s QPSK data using an IQ modulator, and another part was coupled with modulated QPSK signal serving as pump light to generate coherent multi-tone pump lights. The generated QPSK signal was further modulated by a phase modulator driven by an arbitrary waveform generator (AWG) to add phase noise. The degraded QPSK signal was split into two parts using a 10:90 optical splitter. The 90% portion is injected into the phase-sensitive amplifier part to achieve phase regeneration, and the other was directed transmitted to the Kerr comb generation section. The degraded signal is coupled with the continuous wave (CW) laser beam using a 10:90 optical splitter and is used to model all-optical carrier recovery for Kerr comb generation. The OCSR of the signal can be adjusted using the variable light attenuator. After amplification by the low-noise erbium-doped fiber amplifier (EDFA), the two comb teeth at 1549.2 nm and 1552.4 nm were filtered using a wavelength selective switch (WSS) as $P_1$ and $P_2$, respectively. The signal attenuated differently between $P_1$ and $P_2$ to meet the power requirements of subsequent phase-sensitive amplification. Subsequently, these two pump light beams were transmitted to the phase-sensitive amplifier part.

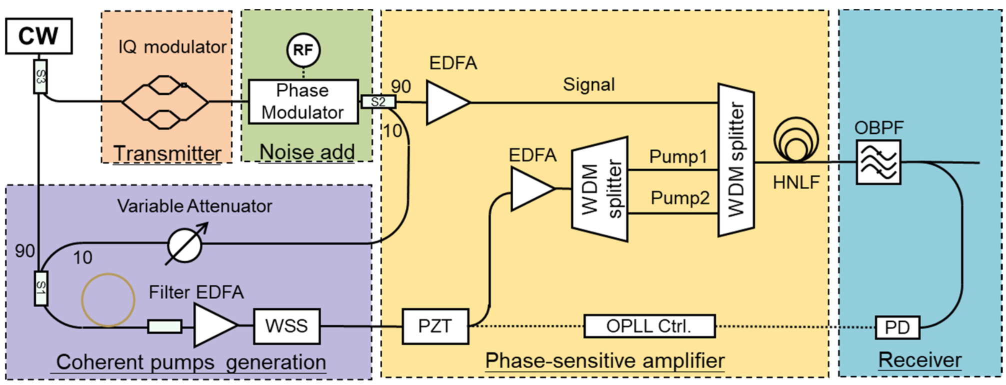


**Figure 2.** The experimental setup of single-step phase-sensitive regeneration of QPSK. RF: Radio Frequency; S1 and S2: 10:90 optical splitter; S3: 3 dB splitter.

In the phase-sensitive amplifier module, the dual-pump beams are initially amplified by an EDFA. Next, the amplified dual-pump is coupled with the amplified degraded signal by using a wavelength-division multiplexer (WDM). This step eliminates the out-of-band noise arising from amplified spontaneous emission (ASE) noise. Finally, the combined laser beams are injected into the highly nonlinear fiber (HNLF) with signal power of 20 dBm and dual-pump power of 14 dBm. After regeneration, the regenerated signal at 1551.6 nm is filtered out by an optical bandpass filter and is split into two parts by a 3 dB splitter. One path is converted to an electrical signal using photodetectors (PD) and then fed back to the dual pump via an electromagnetic amplification and locking circuit via the piezoelectric ceramic. The feedback loop eliminates low-frequency phase jitter caused by environmental noise, allowing for phase match of the signal and pumps, resulting in ideal regeneration. It is note that the relative phase between the dual-pump and signal can be precisely controlled by adjusting the locking point. To ensure stable locking, it is necessary to place the entire experimental setup on a shockproof platform and secure it firmly. Additionally, the environment temperature fluctuation will result in lost locking state, so controlling the room temperature is also crucial for phase regeneration. The other path of regeneration signal has been detected using an optically coherent receiver followed by oscilloscope. And the signal constellation diagram and the signal-to-noise ratio (SNR) have been measured via digital signal processing (DSP) to accurately quantify the phase noise.

## 3. Results

In order to provide a clearer demonstration of the phase-sensitive effect, Figure 3c,d displays the input and output spectra of the HNLF. Our experimental results demonstrate that, in the unlocked state, the regeneration signal experiences a phase jitter of 3 dB at the idle frequency caused by the random changes in the phase difference between the signal and the dual-pump due to ambient noise. These observations validate the occurrence of the phase-sensitive amplification process. The optical spectrum of the Kerr soliton comb can be observed in Figure 3b. We adopt one $Si_3N_4$ micro-ring resonator for Kerr soliton comb generation. The cross-section of the microcavity is $1650 \times 800$ nm$^2$, and the FSR is around 100 GHz. The $Si_3N_4$ chip is packaged with polarization-maintaining I/O fibers and is shown in Figure 3a.

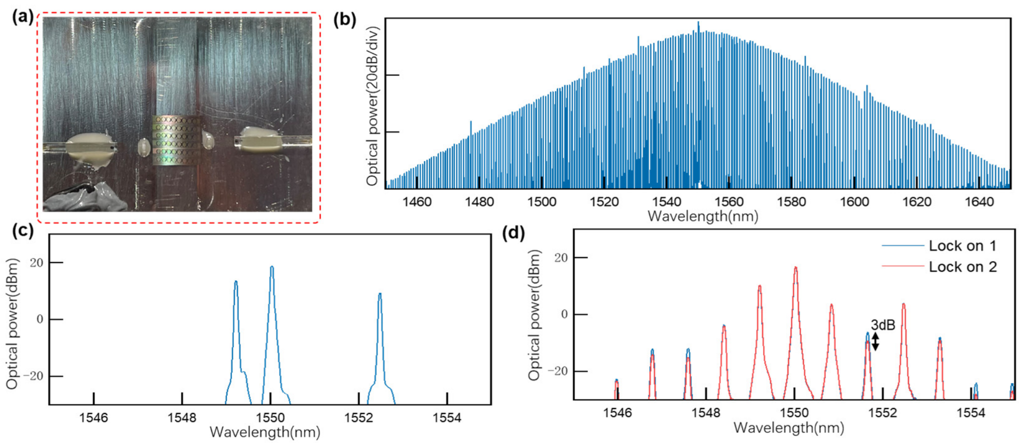


**Figure 3.** (**a**) The pictures of packaged $Si_3N_4$ chips used in our experiment. (**b**) Measured optical spectrum for Kerr soliton comb, which is generated in the part of coherent pump generation. (**c**) The input spectrum of the HNLF. (**d**) Output spectrum under conditions that satisfy different phase matching between the signal and the pump. The regeneration signal experiences a phase jitter of 3 dB at the idle frequency.

Our experimental results indicate that the regeneration effect is highly reliant on the frequency match between the dual-pump and the signal. The regeneration process takes place via the superimposition of the $3\varphi_s$ idler and the $-\varphi_s$ idler; thus, the closer the frequencies of these two idler light beams, the greater the regeneration effect. Our study found that variations of the OCSR in carrier recovery had only a minor effect on the frequency stability of the comb but did affect the phase regeneration effect. Figure 4 illustrates the constellation diagrams of the 8 GBaud/s QPSK signal at different OCSRs in the carrier recovery, with varying levels of phase noise. Our experiment showed a significant QPSK phase regeneration effect, leading us to conclude that the OCSR in carrier recovery has a substantial impact on the regeneration effect.

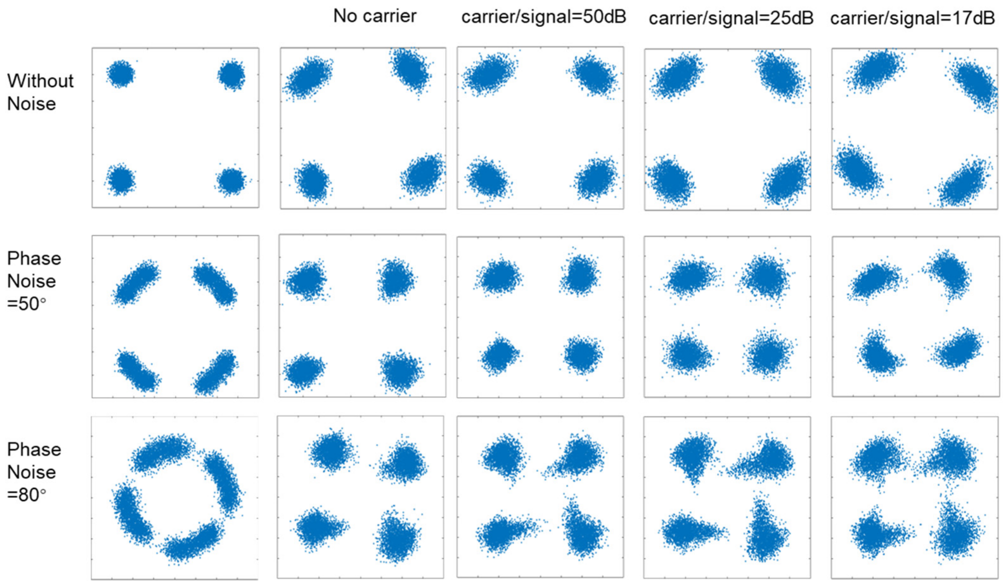


**Figure 4.** Constellation diagrams of different input carrier ratios with no noise, 50 degrees of phase noise, and 80 degrees of phase noise.

In the case of a signal without degradation, the process of phase regeneration introduces amplitude noise due to its underlying mechanism. Highly compressed phase effects lead to the broadening of amplitude noise. The compression of phase noise during phase regeneration is significant when the initial phase noise is between 50 and 80 degrees. However, the phase regeneration process has weaker suppression ability for amplitude noise as the initial phase noise increases. A comparison of the regeneration effect for different OCSRs in carrier recovery shows that a stronger signal carried in carrier recovery results in a weaker compression of phase noise and stronger effects of amplitude noise. This is because a larger OCSR in carrier recovery causes greater disturbances to the frequency stability of the comb, which subsequently affects the coherent addition of the two idlers and impacts the regeneration performance. Nonetheless, such disturbances do not significantly hinder the effect of phase regeneration. Phase regeneration effects can still be observed even when the OCSR is 17 dB. Moreover, when the carrier is 25 dB larger than the signal in carrier recovery, the perturbation caused by the carrier recovery on the comb frequency stability has a minimal effect on the phase noise compression capacity.

In this study, we analyzed the changes in SNR of a 20 GBaud/s QPSK signal with consistent receiver input power under two different levels of phase noise, without a signal being carried in carrier recovery, to better demonstrate the difference in signal quality before and after regeneration. Our experimental results, as illustrated in Figure 5b, reveal an improvement in the sensitivity of the regenerated signal reception by more than 9 dB when compared to the signal before regeneration. Moreover, to eliminate the perturbations caused by the fluctuation of environmental temperature and air flow, we introduced an active electric feedback loop to lock the relative phase between the signal and dual-pump beams. As shown in Figure 5a, the significant response of the electric feedback loop to the perturbations introduced to the link is achieved.

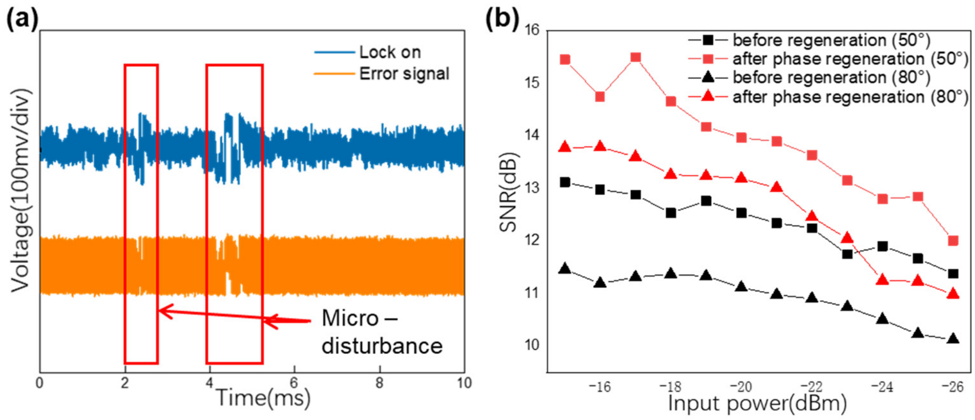


**Figure 5.** (**a**) Servo output signal (blue) and error signal (yellow); (**b**) shows the calculated SNR before (black) and after regeneration (red).

## 4. Conclusions

This paper presents a carrier recovery scheme to generate Kerr soliton combs for the phase regeneration of 20 GBaud/s QPSK signals in an HNLF using a low input dual-pump power of 14 dBm. The approach increases the sensitivity of the received regenerated signal by more than 9 dB at the same receiving SNR. Furthermore, the paper compares the regeneration effects of 8 GBaud/s QPSK signals at 50° and 80° under different OCSRs in carrier recovery. This comparison highlights the frequency stability requirements between the dual pumps for the phase regeneration process. The study simplifies the existing experimental architecture of phase regeneration based on HNLFs while demonstrating exceptional regeneration performance. Additionally, this work addresses the recovery problem of the Kerr comb in practical communication processes and proposes a regeneration scheme that can be used for quality recovery in long-distance all-optical communication in the future.

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**Data Availability Statement:** The data presented in this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

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