Experimental Demonstration of All-Optical Phase Noise Mitigation of 40-Gbits/s QPSK Signals by Mixing Differentially Delayed Nonlinear Products

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Abstract: We propose and demonstrate an all optical phase noise mitigation scheme by mixing differentially delayed nonlinear products. For 40-Gbits/s signals, phase squeezing results in phase noise range reduction of around 50% and 1.5 dB OSNR gain at BER 10^{-5}.

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1. Introduction

Coherent optical communication systems are of critical interest due to their ability to handle higher-order, spectrally efficient modulation formats. In particular, quadrature phase-shift-keying (QPSK) has become extremely popular for currently deployed 25-Gbaud, pol-muxed 100-Gbits/s systems [1]. For such systems, phase noise due to Kerr nonlinearity represents a key limitation of system performance [2, 3]. Therefore, approaches to mitigating phase noise on an optical data channel have been of interest to the community [2].

Nonlinear phase noise can be partially compensated by electronic signal processing techniques in a coherent receiver [4, 5]. However, there might be motivation to perform phase noise mitigation optically in order to either limit the optical-to-electronic conversion as well as potentially enable higher baud rates [6].

Optical phase noise mitigation has been reported using different variations of a phase-sensitive-amplifier-based approach to achieve a level of “phase squeezing” [6-10]. However, these methods tend to require coherency between a data signal and a pump, thereby typically necessitating phase-based feedback loops and injection locking [6-10].

We propose and demonstrate an all optical phase noise mitigation scheme by mixing differentially delayed nonlinear products. Utilizing differentially delayed signal and its conjugated third harmonic, phase noise is suppressed. Improvement on the system performance is successfully verified by constellation analysis, the error-vector-magnitude (EVM), and the bit error rate (BER) measurements. For 40-Gbits/s signals, phase squeezing results in phase noise range reduction of around 50% and 1.5 dB OSNR gain at BER 10^{-5}.

2. Concept

Fig. 1 depicts the conceptual block diagram of our phase noise mitigation approach. A quadrature-phase-shift-keyed (QPSK) signal with phase Φ_s, along with a CW pump (with phase Φ_p), are injected into a periodically-poled-lithium-niobate (PPLN) waveguide to generate a phase conjugate copy of the original signal (with phase $2\Phi_p$-Φ_s). The signal and the conjugate copy are then sent into a highly nonlinear fiber (HNLF) to generate the third harmonics of the signal with phases $-2\Phi_p+3\Phi_s$ and $4\Phi_p-3\Phi_s$. To suppress the phase noise of the signal, a staircase phase transfer function can be composed from the signal and its conjugated third harmonic [8]. This requires that the signal and the conjugated third harmonic are coherent and phase-aligned. In our scheme, the differentially delayed of the signal and its harmonics create the elements of the transfer function coherent and phase aligned. After the HNLF, the signal and harmonics are sent into an in-line spatial light modulator (SLM) phase and amplitude programmable filter to apply appropriate delays, amplitudes, and relative phases. The adjusted signal and harmonics with a CW pump are injected to another nonlinear stage that coherently mixes products of the signal with its conjugate, and the third harmonic with its corresponding conjugate. If needed, the output can be wavelength converted back to the input signal wavelength using common all-optical wavelength conversion methods. The output of the system is a staircase phase transfer function, that is, $\exp(j\Delta\Phi_s) + m\exp(-j3\Delta\Phi_s)$ where $\Delta\Phi_s = \Phi_s(t) - \Phi_s(t-T)$, and T refers to one symbol interval of the signal. Fig. 1(a) shows the quantization behavior of the output phase of the phase transfer function versus $\Delta\Phi_s$. The value of m can be optimized in the second SLM filter and is approximately between 0.3 and 0.5 [9]. Here, $\Delta\Phi_s$ is the simple encoded version of the original signal and has the same format as a differential phase shift keying modulation. This modification of the input encoding can be compensated by appropriate precoding at the transmitter, considering the number of our squeezing systems in the path. If the value of m is set to zero, the scheme is simplified to that of reference [11]. In this case, the output function, $\exp(j\Delta\Phi_s)$, is a high-pass filter on the input phase which can alleviate only phase noise with low bandwidth power spectral density [11].

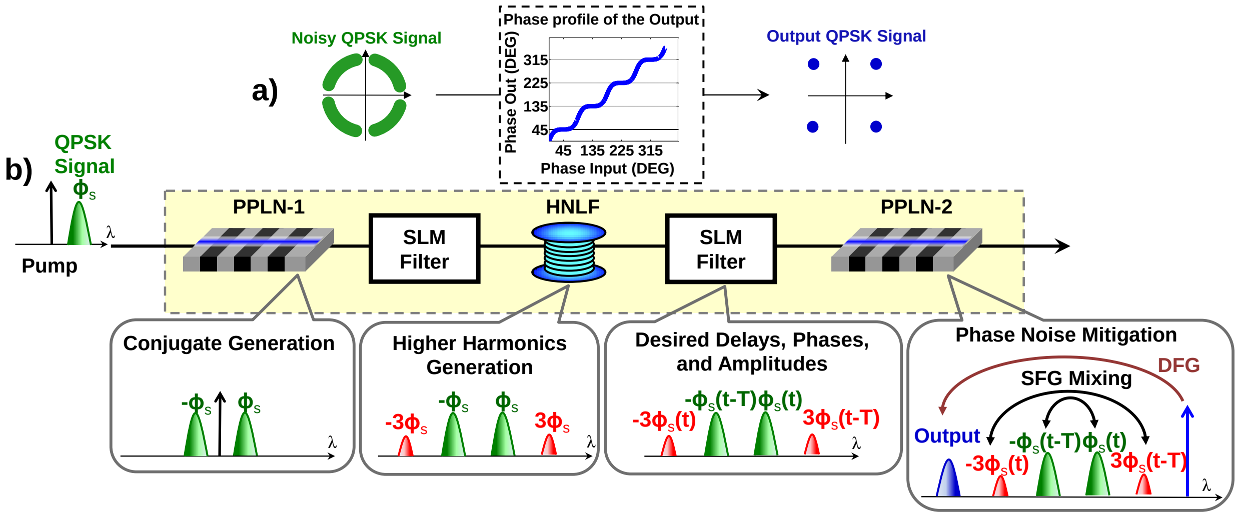

Fig. 1. The concept of the phase noise mitigation scheme. (a) The phase noise of the input signal is squeezed based on the stair case phase transfer function of the system, i.e., phase of $\exp(j\Delta\Phi_s) + m\exp(-j3\Delta\Phi_s)$. (b) The signal conjugate copy is generated in PPLN-1. The first SLM adjusts the amplitudes and removes the pump. In HNLF, the signal and the conjugate copy generate the third harmonics through the dengenerate FWM process. The second SLM Filter applies appropriate delays, phases, and amplitudes to the signal and other nonlinear products. Finally, PPLN-2 coherently mixes products of the signal with its conjugate, and the third harmonic with its corresponding conjugate in the output.

3. Experimental Setup

The experimental setup for the phase noise mitigation scheme is illustrated in Fig. 2. A nested Mach-Zehnder modulator is used to generate 20-Gbaud QPSK data (pseudo-random bit sequence (PRBS) of length 2^{31}-1). This input signal is amplified by an EDFA and phase modulated with an amplified spontaneous emission (ASE) source to emulate phase noise. Various levels of phase noise can be generated by adjusting the variable optical attenuator (VOA) before the photo detector (PD). The noisy signal is amplified and coupled with an amplified CW pump around 1551.5 nm and injected into the PPLN-1 waveguide in order to generate the phase conjugate of the signal. The PPLN-1 output is sent to a spatial light modulator (SLM) phase and amplitude programmable filter based on liquid crystal on silicon technology for adjusting amplitudes. The adjusted signal and its conjugate copy are amplified and sent to a 450-m HNLF (with 1555 nm zero dispersion wavelength) to generate the third harmonics of the signal through the degenerate four-wave mixing (FWM). The signal and the generated harmonics are sent to another SLM filter to apply appropriate delays, amplitudes, and relative phases. The resulting signals are amplified and coupled with another CW pump around 1558 nm and sent to the PPLN-2 waveguide to mix the signal and its conjugate copy and also the third harmonic and its conjugate through cascaded processes of second harmonic generation followed by difference frequency generation (cSHG-DFG). Finally, the output signal is captured by a coherent detector to measure the phase noise range, error-vector-magnitude (EVM), and bit error rate of the system.

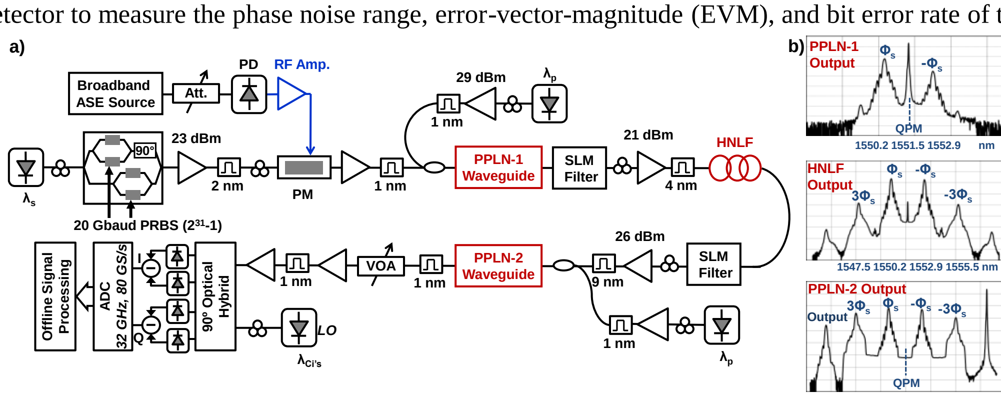

Fig. 2. (a) Experimental setup. PM: Phase modulator, HNLF: Highly nonlinear fiber, PPLN: Periodically poled lithium niobate, SLM: Spatial light modulator, PD: Photo detector, VOA: Variable optical attenuator, LO: Local oscillator. (b) Optical spectra of PPLN-1, PPLN-2, and HNLF.

4. Results and Discussion

The performance of the system is assessed using 20-Gbaud QPSK signals. The proposed scheme is bit rate transparent, so the results at this baud rate should also approximately apply to other rates. Fig. 3 shows the input and output constellations, with various levels of phase noise. The phase noise reduction is significant, particularly for high levels of phase noise. For comparing the phase noise range between various constellation diagrams in Fig. 3(a), the parameter δ_ϕ is defined which quantifies the phase deviation from the corresponding expected values. For the input signals with high phase noise levels, Fig. 3(a,b), the scheme effectively reduced the phase noise in the output signals (δ_ϕ decrease around 50%). Fig. 4(a) summarizes the percentage of phase noise range reduction between the input and output signals for various levels of phase noise. As shown in Fig. 4, the phase noise reduction and error-vector-magnitude (EVM) improvement is more significant for the constellations with higher amount of phase noise.

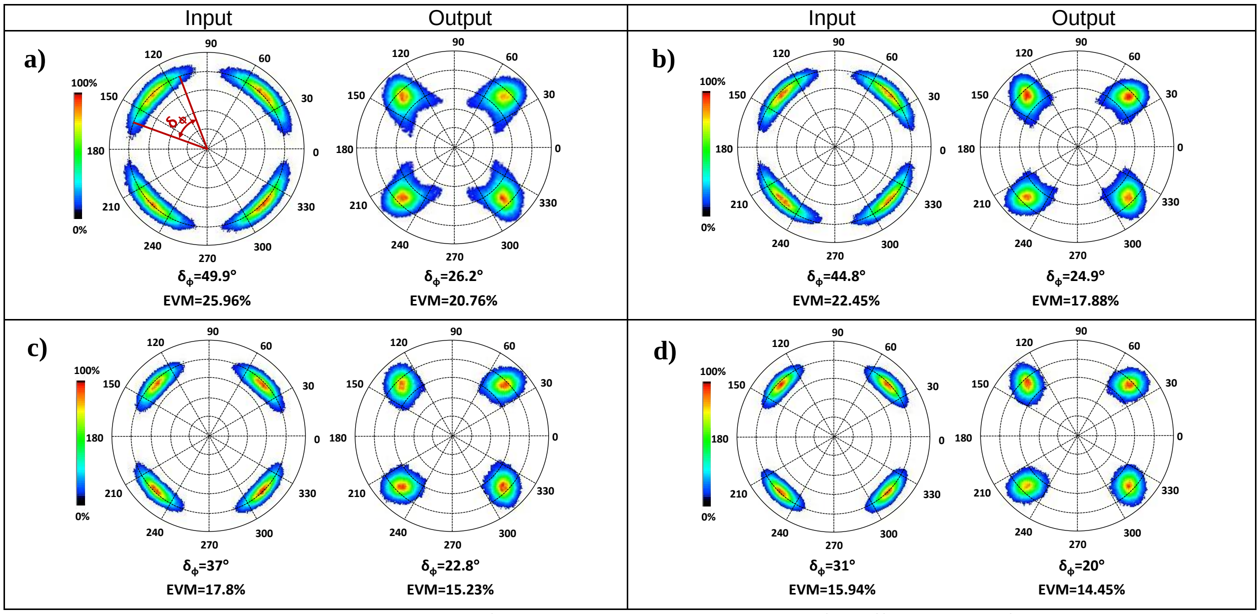

Fig. 3. The input and output constellation diagrams of the phase noise mitigation systems for different levels of phase noise: (a) very high (δ_ϕ=49.9º) (b) high (δ_ϕ=44.8º), (c) medium (δ_ϕ=37º), and (d) low phase noise (δ_ϕ=31º).

Fig. 4 (b) shows the bit error rate (BER) of the phase noise mitigation system for two different levels of phase noise, $\delta_\phi \sim$ 40° and 33°. The scheme results in 1.5 dB optical signal to noise ratio (OSNR) gain at a BER of 10^{-5}.

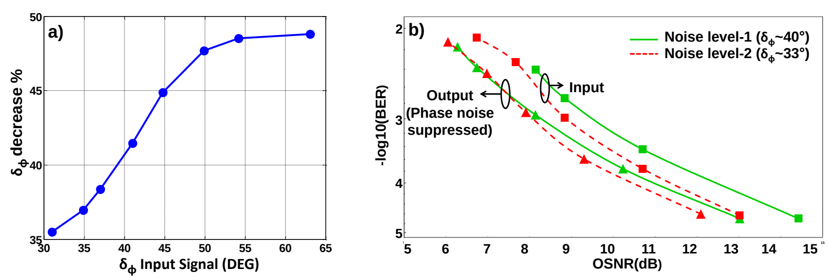

Fig. 4. System performance. (a) Percentage of phase noise range reduction between the input and output signals for various levels of phase noise. Phase noise reduction is more significant for higher levels of phase noise. (b) BER versus OSNR for two different levels of phase noise (δ_ϕ~40°, 33).

Acknowledgements

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