All-Optical Phase Noise Suppression Using Optical Nonlinear Mixing Combined with Tunable Optical Delays

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Abstract: We propose and demonstrate an all-optical scheme of phase noise reduction using optical nonlinearity and dispersion/conversion delay. This scheme is capable of reducing the standard deviation of phase noise with low frequency component (e.g., laser phase noise) by a factor of ~ 4 without degrading the data signal. The EVM can be reduced from 31% to 11% for ~500 MHz phase noise bandwidth on 20-Gbaud QPSK input.

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1. Introduction

Coherent optical communication systems have emerged in the last several years as a compelling approach for enhanced data transmission performance.[1] Moreover, advanced modulation formats that employ various forms of phase-shift-keying (PSK) (e.g., bipolar and quadrature PSK) represent some of the most popular approaches in coherent systems.[1, 2] A critical limitation of phase-sensitive coherent receivers is the phase noise that exists on the recovered data signal.[1] Important sources of phase noise at the coherent receiver is the laser linewidth of the transmitter laser as well as of the receiver local oscillator;[3,5] note that additional sources can include nonlinear phase noise created by amplified spontaneous emission interacting with the nonlinear Kerr effect.[8]

Typically, an optical receiver might include special circuitry and signal processing algorithms to help recover the carrier phase and partially mitigate the laser-linewidth-induced phase noise.[1,2] A desirable goal might be to reduce the effect of linewidth-based phase noise in coherent receivers using high-data-rate optical approaches, which might produce higher speed and wider dynamic range performance.

In this paper, we propose and demonstrate an all-optical scheme of phase noise reduction using optical nonlinear mixing and tunable optical delays. Utilizing the phase conjugate copy of original signal, the standard deviation of the phase noise, caused by the laser linewidth, can be reduced by a factor of ~4. The EVM can be reduced from 31% to 11% for ~500 MHz phase noise bandwidth on 40-Gbit/s QPSK signal.

2. Concept

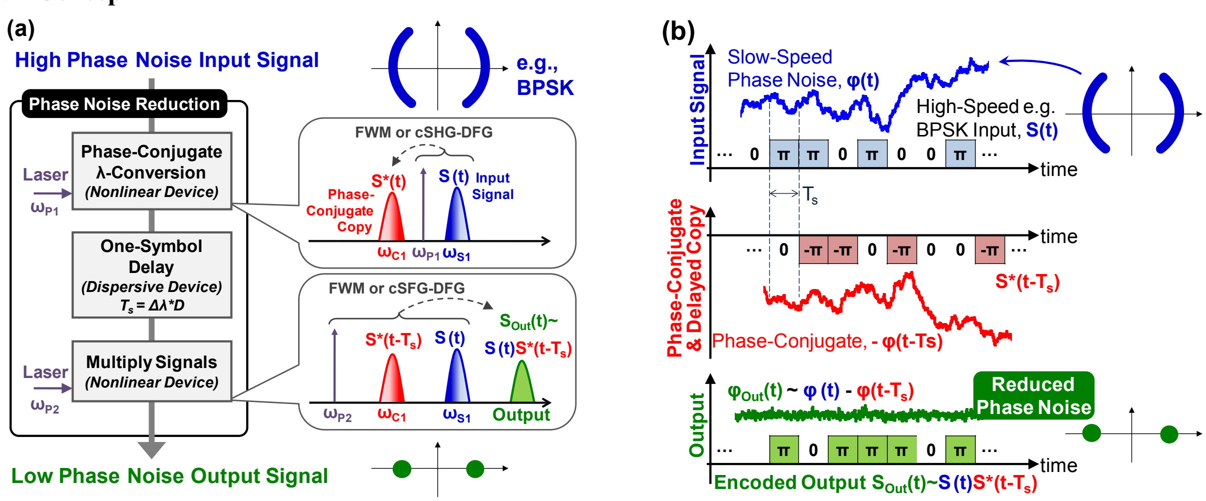

Fig. 1. (a) Concept of the phase noise reduction scheme: PSK input signal is multiplied by its one-symbol-delayed phase-conjugate copy to suppress the input signal phase noise. (b) Example of a BPSK input, delayed phase-conjugate copy and output in the time domain, where one-symbol delay is small for the slow phase noise, but large enough to delay the data.

The conceptual block diagram of the proposed phase noise reduction scheme is shown in Fig. 1. In this scheme, first, quadrature-phase-shift-keyed (QPSK) or binary-phase-shift-keyed (BPSK) signal along with CW pump are injected into a PPLN waveguide to produce a phase conjugate copy of the original signal. The signal and its conjugate copy are then sent into the delay stage, in which a DCF spool induces one bit delay between them. Therefore, if the original signal can be denoted by $E(t) = A \times e^{j\varphi(t)}$ and the injected CW laser is $E_{CW} = A_{CW}e^{j\varphi_0(t)}$, the conjugate copy at the DCF output is $|E_{CW}|^2 E^*(t-\tau) \propto A' e^{-j\varphi(t-\tau)}$. These signals (i.e., original signal and the conjugate copy) are then sent to the second nonlinear stage in order to create the mixing product of signal and the copy. This can be denoted as $e^{-j\varphi(t-\tau)} \times e^{j\varphi(t)} = e^{j(\varphi(t)-\varphi(t-\tau))}$. Assuming both CW lasers have negligible phase noise compare to the original signal. Thus, the output phase is $\varphi_{out}(t) = \varphi(t) - \varphi(t-\tau)$. Since the phase of the original signal consists of both data and the phase noise which can be shown as $\varphi(t) = \varphi_D(t) + \varphi_N(t)$, then $\varphi_{out}(t) = [\varphi_D(t) - \varphi_D(t-\tau)] + [\varphi_N(t) - \varphi_N(t-\tau)]$. The first bracket is only a decoding of the original data, which is similar to the differential phase shift keying modulation format. The second bracket, on the other hand, can be viewed as a highpass filter on the phase noise which is able to filtered out low frequency component of the phase noise (e.g., laser phase noise). Therefore, this scheme is capable to reduce the effect of phase noise of the original laser or any noise with low bandwidth power spectral density.

3. Experimental Setup

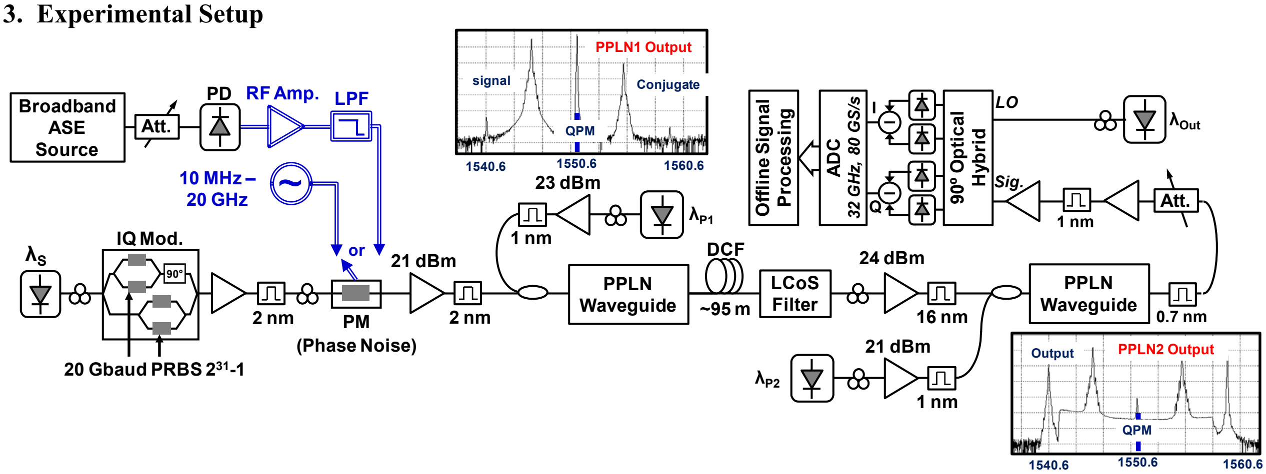

Fig. 2. Experimental setup. HNLF: Highly Nonlinear Fiber, PPLN: Periodically Poled Lithium Niobate Waveguide, SLM: Spatial Light Modulator, DCF: Dispersion Compensating Fiber, PC: Polarization Controller, BPF: Bandpass Filter, ATT: Attenuator, LO: Local Oscillator

The experimental setup for the phase noise reduction scheme is depicted in Fig. 2. A nested Mach-Zehnder modulator is used to generate the 20-Gbaud BPSK and QPSK data (PRBS 2^{31}-1). The resulting signal is amplified in an EDFA and sent to a phase modulator which can be modulated with white noise or a sinusoidal clock. This extra stage in the transmitter is intended for inducing phase noise with different power spectral density and variable power. The signal is then amplified and coupled with an amplified ~1550.6nm CW pump and sent to a periodically poled lithium niobate (PPLN) waveguide in order to produce the phase conjugate of the signal. The signal along with its conjugate are then sent to a ~50 m DCF and a spatial light modulator (SLM) phase and amplitude programmable filter based on liquid crystal on silicon (LCoS) technology for adjusting the amplitudes. The DCF introduces one symbol time relative delay between signal and its conjugate. The signal and the conjugate copy are amplified and coupled with another amplified 1560 nm CW laser and sent to the second PPLN in order to perform mixing between the signal and the conjugate copy. The quasi phase matching (QPM) wavelength of the PPLN waveguide is temperature tuned to QPM of the first PPLN. The mixed signal is detected coherently to measure error-vector-magnitude (EVM) and phase noise. In this figure the spectra of first and second PPLN waveguide are also depicted. As it can be seen the wavelength separation of signal and its copy specifies the delay between them. In this experiment, the delay is tuned to 50ps delay (i.e., 1 bit) which can be easily tuned for different baud rate.

4. Results and Discussion

The performance of the system is assessed by implementing the proposed scheme on 20 Gbaud BPSK and QPSK signals which are degraded by inducing phase noise at different power. In Fig. 3(a), the EVM gain (difference between the EVM of output and input) of the proposed scheme is assessed for different bandwidth of phase noise. As it can be seen, the gain is reduced for larger bandwidth and start to reach less than one for bandwidth larger than 5000 MHz. Fig 3(b) shows the performance of the phase noise reduction scheme on QPSK signal for phase noise with 100MHz, 1000 MHz and 3300 MHz spectral density bandwidth. As it can be seen, the phase noise reduction is significant especially for lower bandwidth. Fig 3(c) shows the performance for different amount of phase noise all at 750MHz bandwidth on BPSK signal. Although the phase noise spectral density bandwidth is fixed at 750 MHZ, the phase noise standard deviation is adjusted for three different values. The output of the system, as it can be seen, shows very little phase noise even for high input phase noise.

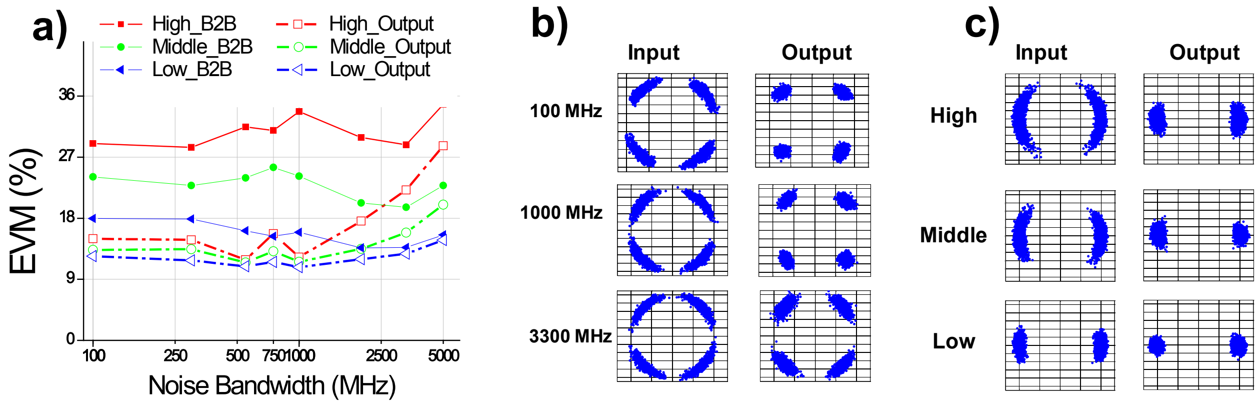

Fig. 3. (a) Experimental EVM reduction amount vs. noise bandwidth for 20-Gbd QPSK input. (b) Phase noise reduction on QPSK signal with phase noise bandwidth of 100MHz/1GHz/3.3GHz and (c) Phase noise reduction on BPSK signal with phase noise bandwidth of 750 MHz for high/middle/low phase noise standard deviation

Here, the reduction factor is defined as the ratio of input phase noise standard deviation over output phase noise standard deviation. In Fig. 4(a) the performance of the system is assessed by measuring this reduction factor in three cases of high, middle and low phase noise for different noise bandwidth. It shows better performance at lower bandwidth and higher reduction factor for higher phase noise.

In Fig 4(b), the EVM gain versus frequency is depicted. In this case, the phase modulator is derived by sinusoidal waveform to illustrate the EVM gain at each frequency component. The EVM gain can be as high as 30% for 100 MHz sinusoidal waveform, decreased dramatically after 1000 MHz and for > 4000 MHz, this gain is less than one. Fig. 4(d), on the other hand, shows the reduction factor for different frequency. For frequency less than 100 MHz this factor can be as high as 6 and ~1 (no gain) for 5000 MHz.

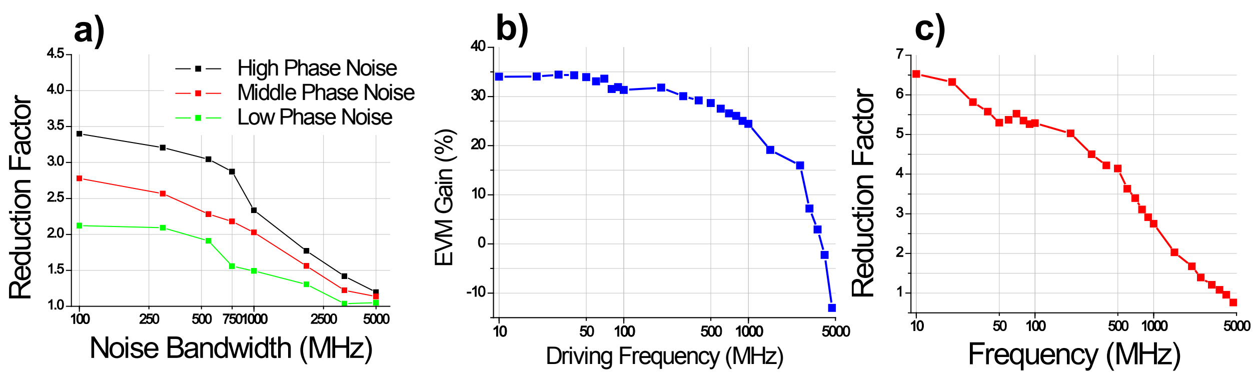

Fig. 4. (a) Experimental phase noise reduction factor vs. noise bandwidth, (b) EVM gain vs. frequency, and (c) reduction factor vs. frequency

Acknowledgements

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4. References

[1] E. Ip, , J. Lightwave Technol., vol. 25, no. 9, pp. 2675–2692, (2007).
[2] A. Demir, J. Lightwave Technol., vol. 25, no. 8, pp. 2002–2032, (2007).
[3] C. Henry , IEEE J. Quantum Electron, vol. 18, no. 2, pp. 259–264, (1982).
[4] J. P. Gordon, and L. F. Mollenauer, Opt. Lett., vol. 15, no. 23, pp. 1351–1353, (1990).
[5] J. M. Kahn, IEEE J. Quantum Electron., vol. 10, no. 2, pp. 259–272, (2004).
[6] K. J. Lee, et al, Optics Express, Vol. 17, Issue 22, pp. 20393-20400 (2009)
[7] C. H. Henry, J. Lightwave Technol., vol. LT-4, no. 3, pp. 298–311, (1986).
[8] R. Slavic, Nature Photonics 4, 690–695 (2010)