Nonlinear Phase Noise Reduction for 20-Gbit/s NRZ-QPSK Signals Using InP on SOI Photonic Crystal Nanocavity

T. H. Nguyen(1), M. Gay(1), L. Bramerie(1), K. Lengle(1), C. Peucheret(1), O. Sentieys(2), J.-C. Simon(1), A. Bazin(3), R. Raj(3) and F. Raineri(3),(4)
(1) *FOTON Laboratory, CNRS, University of Rennes 1, ENSSAT, 22305 Lannion, France*
(2) *INRIA / IRISA, Campus de Beaulieu, 35000 Rennes, France*
(3) *Laboratoire de Photonique et de Nanostructures, CNRS, UPR20, 91460 Marcoussis, France*
(4) *Université Paris Diderot, Sorbonne Paris Cité, 75007 Paris Cedex 13, France*
E-mail: Trung-Hien.Nguyen@enssat.fr

Abstract: All-optical nonlinear phase noise reduction using an InP-over-SOI PhC nanocavity is experimentally demonstrated for 20-Gbit/s NRZ-QPSK signals. The phase-preserving intensity-limiting function results in an OSNR penalty reduction of 3.5 dB at a BER of 10^{-3}.

OCIS codes: (230.5298) Photonic crystals; (070.4340) Nonlinear optical signal processing; (060.1660) Coherent communications; (060.2330) Fiber optics communications.

1. Introduction

InP over silicon-on-insulator (SOI) hybrid photonic crystal (PhC) nanocavities are extremely promising solutions for all-optical signal processing thanks to their compact size, low power consumption and high speed operation ability [1]. Moreover, this solution combines CMOS technology with III-V material optoelectronics, allowing various demonstrations, including lasers and switches [2].

Nonlinear phase noise (NPN), in which intensity fluctuations of a signal are converted to phase noise by the Kerr nonlinearity of optical fibers, is a well-known limitation of QPSK transmission at high span input powers. NPN could be compensated in the digital domain, albeit at the cost of increased complexity in coherent receivers. Instead, the limitation of intensity fluctuations has been shown to reduce the accumulation of NPN along fiber links [3]. Several techniques have been proposed for phase-preserving intensity limitation so far. Among those, the use of nonlinear processes in highly nonlinear fibers [4] has a weak integration potential. Saturable absorbers [3] could also be employed, but suffer from high input power requirements. Since intensity limitation would have to be performed on a per-channel basis in wavelength division multiplexing (WDM) systems, compact integratable low-power solutions are desirable.

We have recently demonstrated that InP-over-SOI PhC nanocavities could act as intensity limiters for intensity [5] and phase [6] modulated signals. However, the actual benefit of the intensity limitation function provided by these ultra-compact devices for NPN mitigation has not been evaluated yet. In this paper, NPN mitigation for QPSK signals is demonstrated in a transmission link using a PhC nanocavity based on III-V/SOI hybrid technology for the first time. The limiter performance is estimated in term of bit-error-ratio (BER) measurements. The improvement in receiver sensitivity resulting from the use of the intensity limitation function prior to highly-nonlinear transmission demonstrates the effectiveness of the scheme for 20-Gbit/s QPSK signals.

2. Intensity Limiting Principle

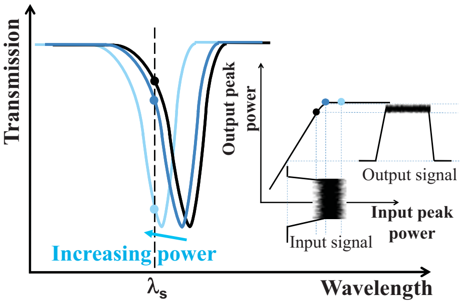

Fig. 1: Nanocavity-based power limiter principle.

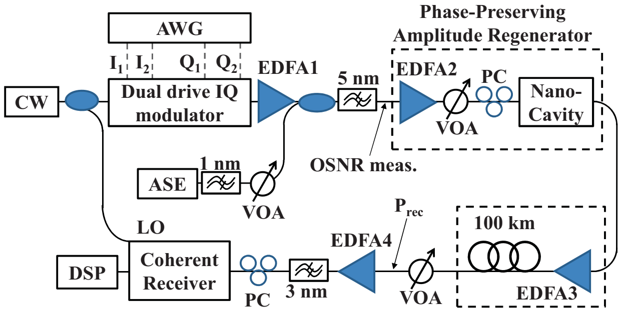

Fig. 2: Experimental setup.

The InP-over-SOI device, which is described in details in Ref. 2, consists of a single-mode SOI wire waveguide evanescently coupled to an InP-based PhC nanocavity. The cavity is of the "nanobeam" type obtained by drilling holes in a single mode InP wire waveguide. The cavity is realized by varying the spacing between holes of the same

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diameter, resulting in a quality factor of the order of 850. A carrier lifetime of 30 ps is furthermore ensured by the use of surface quantum wells [2]. The cavity is fully encapsulated in SiO_2 for efficient heat-sinking. Grating couplers are used at each extremity of the tapered SOI waveguide to enable vertical coupling to cleaved standard single-mode fibers, leading to a total fiber-to-fiber insertion loss (away from resonances) of the device of 12 dB. Fig. 1 illustrates the principle of the intensity limiter function based on nanocavity switching. Upon propagation of an intensity fluctuating signal, the resonance dip of the cavity is shifted towards shorter wavelengths via an intensity-dependent refractive index change induced by an increase of the carrier density. For a signal wavelength tuned to the low frequency side of the cavity resonance dip, the transmission of the cavity is reduced as the signal peak power increases, as illustrated in Fig. 1. In this way, self-switching of the cavity plays the role of an intensity limiter in the presence of intensity variations.

3. Experimental Setup

The experimental setup is represented in Fig. 2. A non-return-to-zero (NRZ)-QPSK signal at 10 Gbaud is generated by applying 2 pseudo-random binary sequences (PRBSs) to an in-phase/quadrature (IQ) modulator. The PRBSs of length 2^{23}-1 are generated using different primitive polynomials and synthesized using an arbitrary waveform generator (AWG). The IQ modulator output signal is then amplified by an erbium-doped fiber amplifier (EDFA1) and bandpass filtered. Intensity noise is added prior to nonlinear transmission by degrading the optical signal-to-noise ratio (OSNR) of the modulated signal. This is achieved by noise loading the signal with the output of an amplified spontaneous emission (ASE) source followed by a 1-nm optical band-pass filter (OBPF) and a variable optical attenuator (VOA). At the input of the regeneration stage, the power of the signal is adjusted to 9 dBm by EDFA2 followed by a variable optical attenuator (VOA). The degraded QPSK signal then enters the nanocavity-based intensity limiter with its state-of-polarization (SOP) adjusted to the TE mode of the waveguide thanks to a polarization controller. The center wavelength of the signal is slightly blue-shifted with respect to the linear cavity resonance in order to enable the previously described intensity limiting function. To be able to compare the transmission performances of the noise-loaded and intensity-limited signals in a fair way, a polarizer aligned with the signal SOP is used in place of the nanocavity in the former case.

The OSNR degradation at the transmitter side allows the generation of NPN after injecting the signal with a high power to the subsequent optical fiber link. The signal power is boosted up to 17 dBm by EDFA3 before being launched to 100-km non-zero-dispersion-shifted fiber (NZDSF, chromatic dispersion of 4 ps/(nm·km)), in order to emulate the nonlinearities accumulation of a long distance transmission.

At the receiver side, another VOA followed by EDFA4 and a 3-nm OBPF are used in order to adjust the received OSNR for BER measurements. The QPSK signal and the local oscillator (LO) are mixed in an optical 90°-hybrid DP-QPSK integrated coherent receiver. The in-phase and quadrature components are then detected by balanced photodiodes and acquired by a real-time oscilloscope with electrical bandwidth of 16 GHz. Finally, post-processing is performed offline using the Matlab environment after data acquisition at 20 GS/s. It should be noted that the same laser, operating at 1557 nm with a linewidth of 100 kHz, is utilized at the transmitter and as local oscillator (LO) in order to simplify the setup by avoiding any impact from other functionalities implemented in the digital signal processing (DSP). In particular, carrier frequency offset compensation is eased.

In the first step of digital processing, an adaptive finite impulse response (FIR) filter [7] operating at twice the symbol rate is used as equalizer and applied to blocks of 20000 symbols. After stabilization of the feedback loop of the equalizer, the received samples are decimated to a symbol rate of 10 GS/s for the following processes. Phase estimation is performed by applying the widely-used Viterbi-Viterbi algorithm on blocks of 10 samples. Moreover, the first 5000 samples are processed to minimize the BER in order to remove phase ambiguities. A comparison between the decoded bit sequence and the transmitted one is then performed to determine the BER over 4 million samples. The impact of NPN on the phase information is also characterized through phase distribution analysis.

4. Results and Discussion

Fig. 3 represents the constellations of the received samples, as well as the corresponding normalized distributions of the phase obtained by elevating the processed complex signal samples to the fourth power in order to suppress the phase data information and superimpose all symbols at the same phase angle. Fig. 3(a) and (d) correspond to the back-to-back (B2B) case (no transmission and no intensity limitation) for a received OSNR (over 0.1 nm) of 18 dB. Fig. 3(b) and (e) are obtained after transmission over 100 km without the intensity limiter for an OSNR at the link input of 18 dB and a received power of -20 dBm. The observed dispersion of the constellations and broadening of the phase distributions are due to NPN. Finally, Fig. 3(c) and (d) are obtained after transmission over 100 km in the regenerated case under the same input OSNR and power conditions, showing a less dispersed constellation and a narrower phase distribution.

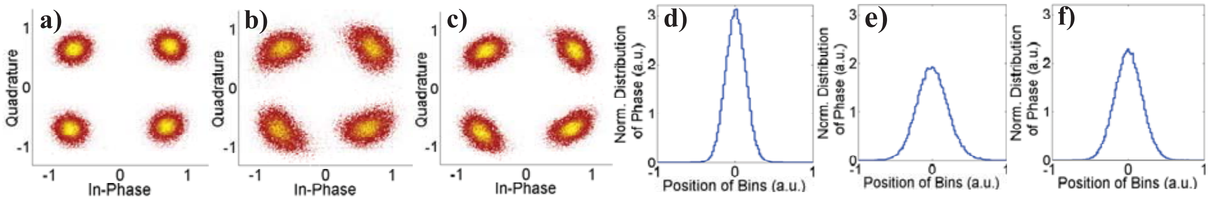

Fig. 3: Constellations and phase distributions at a transmitted OSNR of 18 dB for (a), (d): back-to-back; (b), (e): 100 km transmission without intensity limitation, and (c), (f): 100 km transmission with intensity limitation.

Fig. 4 presents the results of BER measurements as a function of received power in different cases. Back-to-back curves were measured for transmitter OSNR values of 18 dB and 33 dB. Linear phase noise due to ASE is dominant in the former case, as shown by the power penalty of 3.4 dB at a BER of 10^{-3}. After transmission without prior intensity limitation, an error floor at a BER of 10^{-3} is obtained when the input OSNR is 18 dB, showing that the link is indeed limited by NPN. When the intensity limiter is applied, the BER floor for an input OSNR of 18 dB is reduced by two orders of magnitude. This demonstrates that NPN is reduced, proving the efficiency of the device for limiting the impact of intensity fluctuations due to OSNR degradation before non-linear transmission. Finally, Fig. 5 shows the results of BER measurements as a function of the transmitter OSNR for a constant received power of -20 dBm with (circles) and without (squares) regeneration, showing a BER improvement over the entire considered OSNR range. Moreover, the required OSNR for a BER of 10^{-3} is relaxed by more than 3.5 dB thanks to the device.

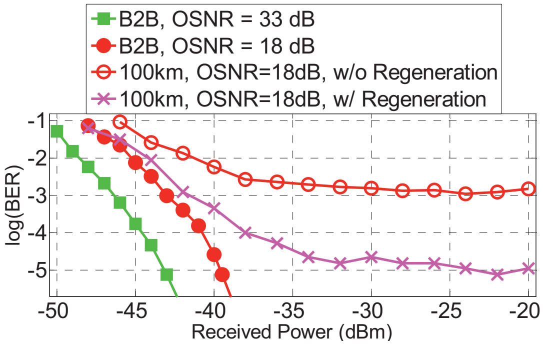

Fig. 4. BER curves back-to-back and after transmission without and with intensity limitation for input OSNR values of 18 dB and 33 dB.

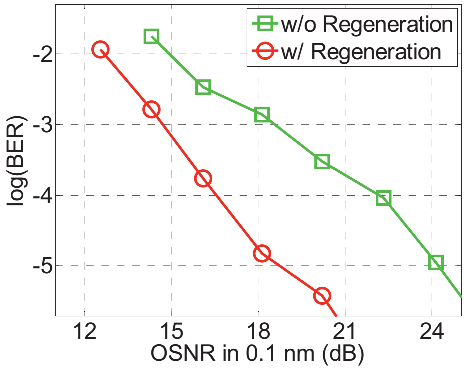

Fig. 5: BER versus input OSNR (P_{rec} = -20 dBm).

5. Conclusions

We have experimentally demonstrated NPN mitigation using an all-optical phase-preserving intensity limiter implemented with an InP-over-SOI nanocavity. At a BER of 10^{-3} error floor suppression was achieved and the required OSNR was relaxed by more than 3.5 dB for 20-Gbit/s NRZ-QPSK signals transmitted over 100 km, demonstrating the effectiveness of the intensity limiter.

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