Silicon Photonics Integrated Circuits for Nonlinear Fourier Transform Based Transmission

A. Moscoso-Mártir(1), J. Koch(2), J. Müller(1), A. Tabatabaei Mashayekh(1), A. D. Das(1), F. Merget(1), S. Pachnicke(2), J. Witzens(1)

(1) Institute of Integrated Photonics, RWTH Aachen University, Campus Blvd. 73, 52074 Aachen, Germany, amartir@iph.rwth-aachen.de
(2) Chair of Communications, Faculty of Engineering, Kiel University, Kaiserstraße 2, 24103 Kiel, Germany, jonas.koch@tf.uni-kiel.de

Abstract *We demonstrate a silicon photonics transmitter capable of modulating and optically merging solitons with reduced electronic constraints. Transmission over 3800 km and 5400 km has been experimentally shown for 2 Vpp and 4 Vpp drive voltages, respectively, without significant penalties between 2-channel and 4-channel configurations.*

Introduction

The capacity of fiber-optic communication systems is ultimately limited by nonlinear distortions such as self-phase modulation (SPM) due to the Kerr-effect, which occur at high signal powers[1]. To increase the capacity beyond the nonlinear limit, sophisticated DSP algorithms such as the digital back-propagation[2], nonlinear equalizers[3] and more recently neural networks[4] have been proposed to reduce the impact of nonlinearities. Another way to handle the Kerr effect is provided by the nonlinear Fourier transform (NFT)[5-7]. The NFT is based on invariant eigenvalues of auxiliary operators (Lax pairs) related to the nonlinear Schrödinger equation[8], found by Zhakharov and Shabat[9]. When working with NFT based systems, fiber-nonlinearities are not regarded as a distortion, but rather as an essential part of the transmission channel. The main advantage of these systems is that using the inverse NFT (INFT), the invariant eigenvalues and functions of the eigenvectors (the scattering parameters), which propagate linearly through the fiber-channel in the spectral nonlinear Fourier domain, can be modulated to transmit the information. These eigenvalues are analogous to frequencies of the conventional Fourier transform in the case of the continuous real-valued spectrum[10,11]. Moreover, complex valued eigenvalues λ_i discretely distributed in the complex plane can be used and correspond to solitons in the time domain[12,13]. To use all degrees of freedom given by the NFT, both spectra can be combined[14]. However, transmitting signals generated by an INFT using a fully modulated spectrum leads to higher demands on the system hardware, since complex waveforms have to be generated, pushing both bandwidth and resolution requirements[7].

In this paper, we experimentally demonstrate a new approach to use the NFT with reduced hardware requirements by using a silicon photonics (SiP) integrated circuit to optically create higher order solitons before sending them over long-haul distances. In this way, only first-order solitons have to be generated with lower electronic hardware requirements, thus enabling a more scalable solution[15],[16]. The work covered here only makes use of the discrete part of the spectrum. However, concomitant exploitation with the continuous parts of the spectrum for higher spectral efficiencies is possible.

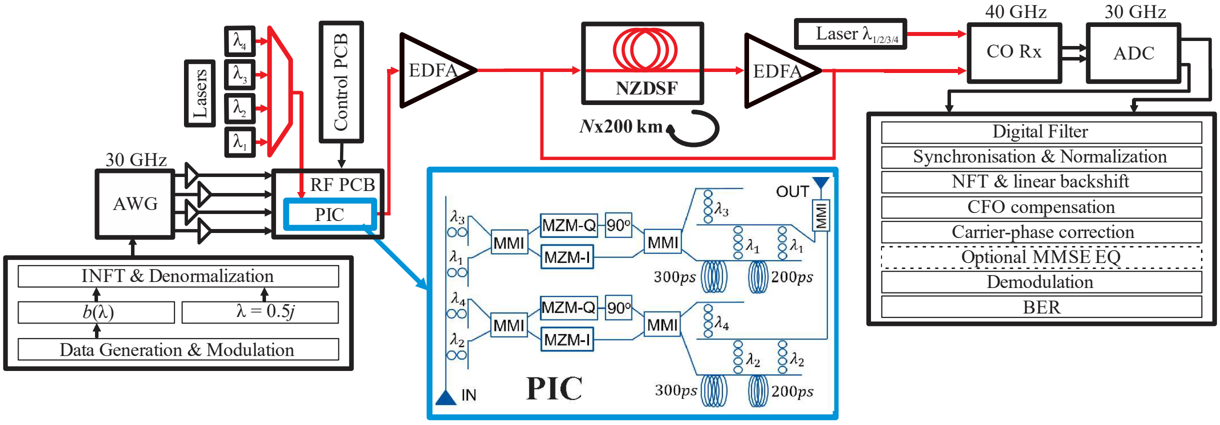

Fig. 1: Block diagram of the investigated link, including an inset with the block diagram of the system PIC.

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

Experimental setup

A block diagram of the overall transmission system is shown in Fig. 1. On the optical side, multiplexed laser lines from discrete cavity lasers are injected in the photonic integrated circuit (PIC) with a fiber array (inset in Fig. 2) to provide the carriers for generating the first-order solitons. On the electrical side, 60 blocks of 2000 first-order solitons, with a bandwidth (BW) of 11.5 GHz (for 99% power), T_{FWHM}=105 ps and 1 GBd per channel are QPSK modulated and generated by an arbitrary waveform generator (Keysight M8196A, 88 GSa/s and 30 GHz BW). Afterwards, the electrical signal is amplified to achieve 4 Vpp or 2 Vpp for 2-channel and 4-channel transmission experiments, respectively, and injected into the PIC with a custom multi-layer RF PCB that has been implemented to make the PIC testable in a system environment (see Fig. 2).

The PIC constitutes the core of the proposed transmitter system, since it implements both soliton modulation and multiplexing. A block diagram of the implemented PIC is shown in the inset of Fig. 1. All its elements can be simultaneously adjusted by a custom-made control PCB comprised of a micro-controller, an array of transimpedance amplifiers (TIAs) for signal acquisition and an array of current sources generating the control signals for thermal phase shifters. Initially, four 2^{nd}-order coupled (ring-) resonator optical waveguide (CROW) optical add-drop multiplexers (OADMs) route the laser carriers to one of the two IQ Mach-Zehnder modulators (MZM). In this configuration, channels 1 and 2 carry, respectively, the same information as channels 3 and 4 (following the labelling of the wavelengths indicated in the inset of Fig. 2). In order to emulate four independent channels, channels 1 and 2 are delayed using 300 ps or 500 ps delay lines that can be selected by using one of two redundant 4^{th}-order CROW OADMs, so that the soliton-to-soliton time spacing can be modified between 150 ps and 250 ps. This also allows to assess the performance of different transmission scenarios. Channels at the output of an IQ modulator are at least two channels apart from each other, present minimal spectral overlap, and are thus routed by the 4^{th}-order CROW OADMs with minimal cross-talk. Finally, a multimode interferometer coupler (MMI) combines the two output bus waveguides, allowing a distortion-less superposition of fundamental soliton pulses even in case of overlapping spectra with nearest neighbor channels, since these are routed in from the two different bus waveguides, at the cost of 3 dB additional insertion losses. More details on the chip architecture and link budget can be found in our previous work[15],[16].

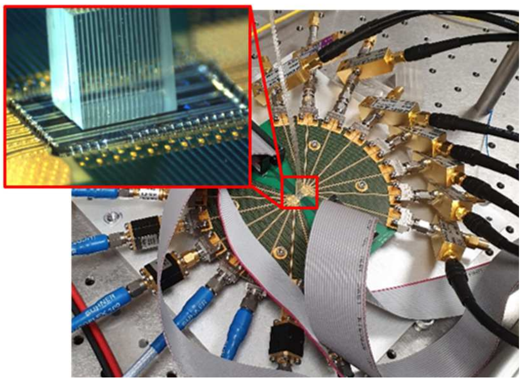

Fig. 2: Photograph of the developed transmitter including an inset of the system PIC attached to the fiber array.

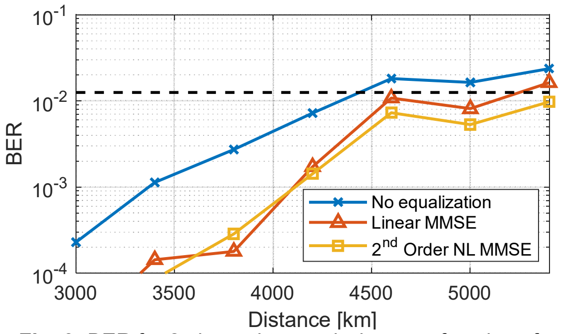

Fig. 3: BER for 2-channel transmission as a function of distance with and without equalization for 4 Vpp drive voltage.

After leaving the PIC, the signal is re-amplified with an EDFA before being fed into a fiber-optical loop consisting of four spans of 50 km True-Wave non-zero-dispersion-shifted fiber (NZDSF) and EDFA amplifiers, to reach an average launch power that fulfills the soliton condition. At the receiver side, the signal is boosted again by a final EDFA, filtered with a bandpass filter (20 GHz optical BW) centered on the channel under test and its polarization adjusted. The signal is then detected by a coherent receiver (Neophotonics µICR-Class 40, 40 GHz BW) using a local oscillator with a 1 kHz linewidth, with its wavelength set to the channel under test. Since we have only one IQ receiver available, we can only receive one channel at a time with maximum bit and sampling resolution. Analog-to-digital conversion is done using a Keysight DSOZ334A oscilloscope (80 GSa/s). After analog-to-digital conversion, the signal is digitally filtered again with a sharper low-pass filter, synchronized and normalized into NFT units. Thereafter, an NFT is employed and the fiber-induced linear phase shift is de-rotated. This is followed by carrier-frequency-offset compensation and phase recovery. An optional (non-)linear minimum mean square error (MMSE) equalization[17], which uses the known deviations of λ (correlated to deviations of the scattering coefficient $b(\lambda)$), is also implemented. Finally, the received $b(\lambda)$ are demodulated, and bit-errors are counted for the detection of the BER.

Results and discussion

For the initial experiments, two channels have been modulated with a 4 Vpp drive voltage and multiplexed with a channel separation of 30 GHz using the 500 ps delay configuration and an aggregated data rate of 4 Gb/s, while the other two laser lines are used only as pilot signals to keep all CROW OADMs aligned with an FSR of 15 GHz. Figure 3 shows the BER as a function of distance before and after equalization is applied. A reach of 4400 km is achieved with BERs below the assumed 14.5% overhead SD-FEC limit of 1.25e-2. These results are clearly improved by applying a linear MMSE and 2nd-order nonlinear MMSE equalizers[17] (2000 training symbols) leading to transmission distances up to 5400 km below the SD-FEC limit.

A second series of experiments has been performed to demonstrate 4-channel transmission. For these measurements, fundamental solitons were interleaved with 250 ps delays and a 15 GHz channel separation, resulting in an aggregated data rate of 8 Gb/s. Due to the limited number of matched RF amplifiers available, when all channels are in use, the same amplifiers have to supply both complementary phase shifters of nested MZMs[18],[19] and the peak amplitude of the delivered RF signals is reduced to 2 Vpp. To separate the penalties due to drive voltage reduction from denser channel packing, the previous 2-channel experiment has been repeated with 2 Vpp (see Fig. 4). Here, independently of the number of channels, a distance of 3,000 km can be reached without equalization with BERs below the used SD-FEC limit. This shows that the utilized four-channel configuration does not yet reach the limits of possible channel packing. Moreover, 4-channel transmission can be also improved by applying a linear MMSE and 2nd-order nonlinear MMSE equalizers, achieving a transmission distance up to 3,800 km below SD-FEC limit (see Fig. 5). With these results, we have demonstrated the feasibility of optical soliton multiplexing in a scalable manner, with reduced requirements for the electro-optical conversion.

Higher data rates up to 16 Gb/s (single polarization) are expected to be achieved with this architecture by further reducing time delays between interleaved solitons and increasing the overall symbol repetition rate (under investigation) and could be further doubled to 32 Gb/s by exploiting both polarizations. Beyond that, the system could further be scaled up by concomitantly exploiting the continuous and discrete nonlinear spectra.

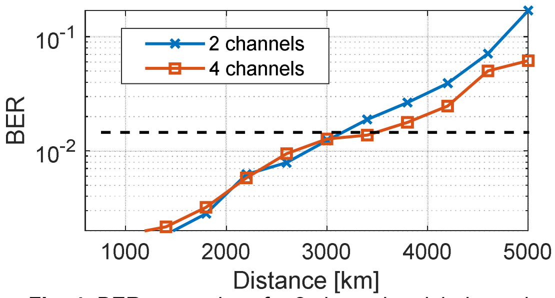

Fig. 4: BER comparison for 2-channel and 4-channel transmission as a function of distance without equalization for 2 Vpp drive voltage.

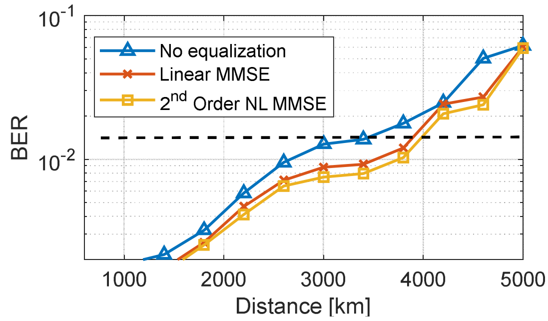

Fig. 5: BER for 4-channel transmission as a function of distance with and without equalization for 2 Vpp drive voltage.

Conclusions

In this paper, we have demonstrated a scalable solution to modulate and merge first-order solitons into higher order solitons in the optical domain by using an SiP transmitter. Experiments with two and four channels have shown data transmission up to 3000 km below the SD-FEC limit without equalization, and up to 3800 km with equalization with a drive voltage of 2 Vpp. Furthermore, the transmission distance can be greatly improved beyond 5000 km by increasing the drive voltage to 4 Vpp. An overall data rate of 8 Gb/s was shown with 4 channels occupying a 60 GHz window (single polarization), which is expected to be extended to 16 Gb/s per polarization, allowing for a spectral efficiency of ~0.5 b/s/Hz in dual polarization, potentially topping off the spectral efficiency achievable with the continuous spectrum. Experiments showing the concomitant exploitation of the continuous and discrete nonlinear spectra are under way, evaluating this technology as a true alternative to traditional transmission systems.

Acknowledgements

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) in the framework of the priority program "Electronic-Photonic Integrated Systems for Ultrafast Signal Processing" by grants PA 1705/1-1 and WI 4137/9-1.

References

[1] R.-J. Essiambre et al., “Capacity Limits of Optical Fiber Networks,” IEEE J. Lightw. Technol., vol. 28, no. 4, pp. 662–701, Feb. 2010.

[2] E. Ip et al., “Compensation of dispersion and nonlinear impairments using digital backpropagation,” IEEE J. Lightw. Technol., vol. 26, no. 20, pp. 3416–3425, Oct. 2008.

[3] Y. Gao et al., “Intra-channel nonlinearities motigation in pseudo-linear coherent QPSK transmission systems via nonlinear electrical equalizer,” Opt. Comm., vol. 282, no. 12, pp. 221–425, 2009.

[4] E. Giacoumidis et al., “Intra and inter-channel nonlinearity compensation in WDM coherent optical OFDM using artificial neural network based nonlinear equalization,” Proc. 2017 Opt. Netw. and Comm. Conf. (OFC), Art. ID Th2A.62.

[5] M. Yousefi et al., “Information transmission using the nonlinear fourier transform, part I-III,” IEEE Trans. Inf. Theory, vol. 60, no. 7, pp. 4312–4328, Jul./Aug. 2014.

[6] S. T. Le et al., “Nonlinear signal multiplexing for communication beyond the kerr nonlinearity limit,” Nat. Photon., vol. 11, no. 9, pp. 570–576, 2017.

[7] S. K. Turitsyn et al. “Nonlinear Fourier transform for optical data processing and transmission: advances and perspectives,” Optica, vol. 4, no. 3, pp. 307–322, 2017.

[8] P. D. Lax, “Integrals of nonlinear equations of evolution and solitary waves,” Commun. Pure Appl. Math., vol. 21, no. 5, pp. 467–490, Sep. 1968.

[9] V. E. Zakharov and A. B. Shabatat, “Exact theory of two-dimensional self-focusing and one-dimensional self-modulation of wave in nonlinear media,” Sov. Phys. JETP, vol. 34, no. 1, pp. 62–69, Jan. 1972.

[10] W. Gemechu et al., “Comparison of the nonlinear frequency division multiplexing and OFDM in experiment,” in Proc. 2017 Europ. Conf. Opt. Comm. (ECOC), Art. ID W.3.C.4.

[11] S. T. Le, H. Buelow, “64 x 0.5 Gbaud Nonlinear Frequency Division Multiplexed Transmissions with High Order Modulation Formats,” J. Lightw. Technol., vol. 35, no. 17, pp. 3692–3698, 2017.

[12] A. Hasegawa et al., “Eigenvalue communication,” J. Lightw. Technol., vol. 11, pp. 395–399, 1993.

[13] S. Hari et al. “Multi-eigenvalue Communication Via the Nonlinear Fourier Transform,” IEEE Int. Conf. on Comp. Intell. and Comput. Res. (ICCIC), Coimbatore, Tamilnadu, India, 2014.

[14] V. Aref et al., “Modulation over nonlinear Fourier spectrum: Continuous and discrete spectrum,” J. Lightw. Technol., vol. 36, no. 6, pp. 1289–1295, 2018.

[15] A. Moscoso-Mártir, et al., “Silicon Photonics DWDM NLFT Soliton Transmitter Implementation and Link Budget Assessment,” in Proc. Europ. Conf. on Integr. Opt. (ECIO), Jun. 2020.

[16] J. Koch, et al., “Experimental Demonstration of a Silicon-Photonics WDM NFT Soliton Transmitter,” accepted at the Opt. Netw. and Comm. Conf. (OFC), Jun. 2021.

[17] J. Koch, et al., “Signal Processing Techniques for Optical Transmission Based on Eigenvalue Communication,” IEEE J. Sel. Top. Quant. Elect. (JSTQE), vol. 27, no. 3, Art. ID 5100214, May-Jun. 2021.

[18] S. Sharif Azadeh et al., “Advances in silicon photonics segmented electrode Mach-Zehnder modulators and peaking enhanced resonant devices,” in Proc. SPIE, vol. 9288, Art. ID 928817, 2014.

[19] F. Merget, et al., “Silicon photonics plasma-modulators with advanced transmission line design,” Opt. Expr., vol. 21, no. 17, pp. 19593–19607, 2013.