Highly Scalable WDM Nonlinear Frequency Division Multiplexed Transmission System using Spectral Overlap

Olaf Schulz[1], Alvaro Moscoso-Mártir[2], Jeremy Witzens[2], and Stephan Pachnicke[1]
[1]*Chair of Communications, Kiel University, Kaiserstr. 2, 24143 Kiel, Germany*
[2]*Institute of Integrated Photonics, RWTH Aachen University, Campus Blvd. 73, 52074 Aachen, Germany*
olaf.schulz@tf.uni-kiel.de

Abstract: We present a highly scalable PIC-based nonlinear frequency division multiplexed transmission system in which b-modulated channels are wavelength division multiplexed with spectral overlap so as to obtain a seamless spectrum without frequency guard bands.

1. Introduction

Increase in the spectral efficiency (SE) of optical fiber transmission systems required to support steady growth in global data traffic is limited by nonlinear fiber distortions due to the Kerr effect [1]. One approach to overcome this limitation are modulation schemes based on the nonlinear Fourier transform (NFT). It maps solutions of the nonlinear Schrödinger equation, which describes the nonlinear propagation of light in an optical fiber, to a nonlinear spectrum that evolves linearly through the optical fiber channel and makes equalization at the receiver simple [2]. As a difference to the well-known linear spectrum, the nonlinear spectrum of an NFT consists of two parts: the continuous (dispersive) part $q_c(\lambda) = b(\lambda)/a(\lambda)$, where λ is the nonlinear frequency, and the discrete (solitonic) part, which consists of a finite number of discrete complex eigenvalues λ_k.

The continuous part of the spectrum can be modulated using orthogonal subcarriers following a transmission scheme called nonlinear frequency division multiplexing (NFDM). This concept has attracted considerable attention in recent years, but still presents many challenges [3]. One of the biggest is the scaling of NFDM systems to the utilization of wide spectra such as the entire C-band. Up to now, most of the performed experiments have been restricted to the electro-optic modulation of a single optical carrier (one channel) and very limited in bandwidth (BW) due to electro-optic hardware limitations [3]. Another challenge arises from the computational complexity of the NFT, which scales as $\mathcal{O}(D \log^2 D)$, with D the number of samples, making it difficult to process large bandwidths or extended time windows [4]. Since there are no nonlinear multiplexers available to combine nonlinear channels while accounting for nonlinear inter-channel crosstalk (ICC), scaling up with increasing the WDM channel count currently requires frequency guard bands between the channels [3], limiting the usable bandwidth and spectral efficiency.

In this paper, we present a new system concept for a WDM NFDM transmission system that does not require frequency guard bands. The proposed solution can be scaled up to large portions of the C-band, limited only by the scalability of the required photonic integration.

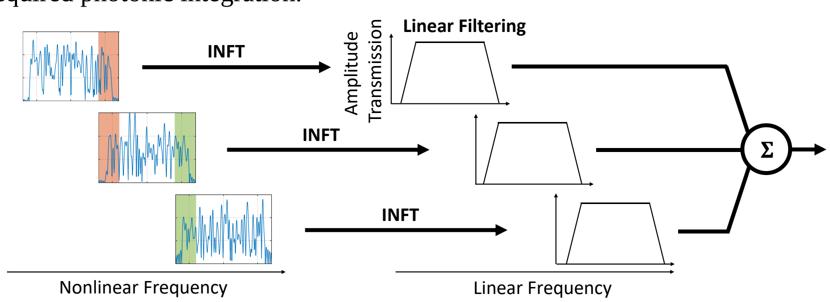

Fig. 1. Illustration of the signal generation flow. Channels are generated independently in the nonlinear Fourier domain by superimposing sinc-shaped spectra corresponding to individual subcarriers. These are identical in the color-coded, overlapping spectral regions, wherein differences in the synthesized nonlinear spectra are due to interferences with adjacent subcarriers. After mapping into the linear domain with an INFT, trapezoid shaped linear filters are applied with the ramp-shaped filter edges summing up to one and located in the spectral overlap regions. Finally, the resulting signals are combined in the optical domain (Fig. 2).

2. System Concept and Setup

When concatenating channels in a WDM system that have been individually processed by the inverse (I)NFT, signal degradation arises from the nonlinear interaction with the neighboring channels that have not been considered during nonlinear processing. Since nonlinear interaction weakens with increased spectral separation [5], this is usually addressed by implementing sufficiently large guard bands. In the absence of guard bands, the outermost subcarriers, closest to the adjacent channels, are primarily affected. Consequently, mitigation has to focus on these and a multiplexing scheme has to be devised that allows taking this inter-channel interaction into account. The solution we propose consists in processing the subcarriers in the boarder-regions with the INFT twice, once as part of the lower frequency channel and once as part of the higher frequency channel, that now overlap in the NFT domain (Fig. 1). In order to combine these channels, after applying the INFT, they are filtered with trapezoidal shaped transfer functions in the linear domain prior to being linearly superimposed. In the overlap region, the launched signal thus results from a combination of taking interaction with both adjacent channels into account, with a relative weight that is set by the shape of the trapezoidal filters and gradually varies to prioritize, for each subcarrier, the interaction with the nearest channel. The linear superposition of the filtered channels is implemented by multiplexing in the optical domain, so that electro-optic modulator bandwidth limitations are adequately addressed. In addition, this allows applying the INFT "by parts" to smaller portions of the spectrum, so that computational complexity is reduced.

Coherently superimposing the overlapping channels is only possible, if they are generated from phase-coherent carriers or phase errors are dynamically compensated. In principle, this can be achieved by using a comb source whose pulse repetition is synchronized with the clock used to generate the electronic signals [6], a unique enabler for joint optical-electrical signal processing. Even then, phase delays introduced by the different optical paths followed by the carriers in the transmitter (Tx) system before multiplexing need to be corrected, which can be done with active phase control (APC) as experimentally demonstrated in [7]. However, the cascaded solution presented in [7] scales poorly with the number of channels due to the ~6 dB losses introduced there in each stage.

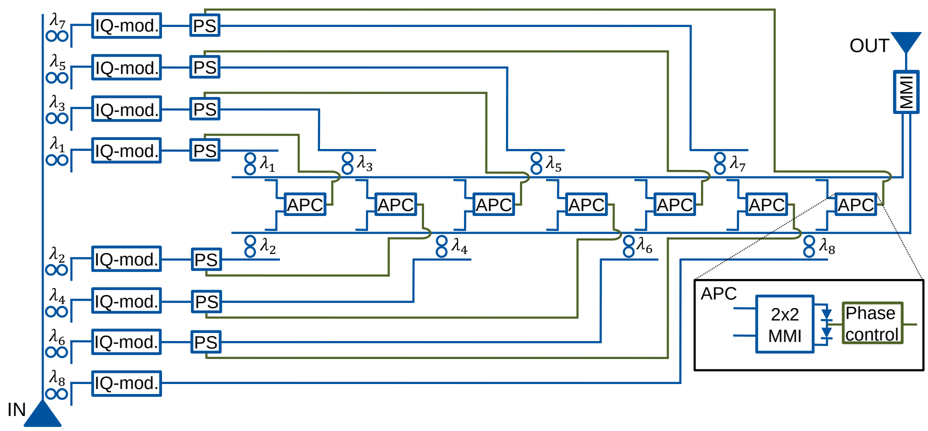

Fig. 2. Block diagram of the proposed Tx PIC for 8 channels.

To enable scalability, we introduce the photonic integrated circuit (PIC) architecture shown in Fig. 2, which is an extension of our PIC that has been successfully used to launch densely packed solitons [8]. In the proposed Tx architecture, the comb laser lines are first demultiplexed using coupled (ring-)resonator optical waveguide (CROW) filters and used as carriers to generate individual channels. After modulation, even and odd channels are injected into two different busses, again with CROW filters, wherein the increased channel separation in each bus allows to do this without spectral overlap and consequently without cross-talk at the optical filters. Finally, all the channels are combined using a 2-by-1 multi-mode interferometer (MMI) that introduces 3-dB excess losses only once, irrespectively of the total channel count. Phase coherence is achieved by setting one channel as the phase reference (channel 8) and using APCs to lock the phase of the other channels recursively from channel 7 to 1. For each APC, only a small portion of the signal (~1%) is tapped from the bus waveguides at a position at which signals from adjacent channels, that are to be phase-aligned, are available to interfere with spectral overlap using a 2x2 MMI. The controlled phase shifter (PS) is adjusted such that the balanced photodetectors at the output of the MMI record equal power. This Tx concept can be scaled up to multiplex a large number of channels with insertion losses stacking up much better than in previous solutions and will be limited primarily by the number of modulators that can be implemented in a chip. The PIC can also be reconfigured to support a different number of channels by tuning in or out the CROW filters.

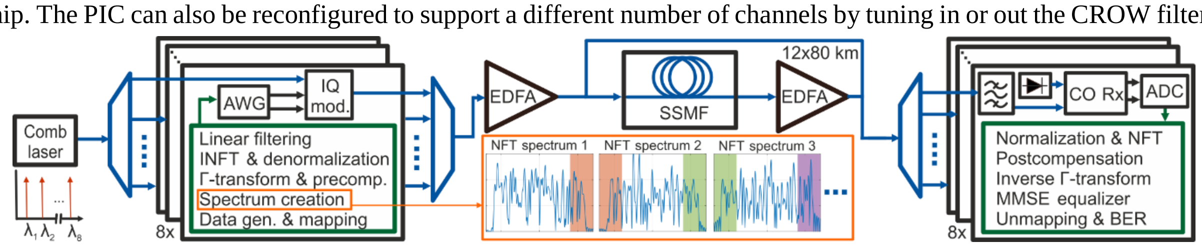

Fig. 3. Block diagram of the simulated transmission system.

Figure 3 shows the simulation setup that has been used to validate the system concept. The overall system has a BW of 200 GHz (centered at 1550 nm) split over 8 channels, each having a BW somewhat in excess of 25 GHz to account for the required overlap. After data generation and mapping to either 16-QAM or 32-QAM symbols, the b-modulated spectrum is created for each channel as a sum of sinc-functions (each corresponding to a subcarrier). After that, a Γ-transform is applied according to [9] to overcome the power limitation of the b-modulation scheme, and dispersion pre-compensation is applied. Finally, the INFT is calculated, trapezoidal-like linear filtering applied, and the modulator drive-signals generated with an 88 GSa/s sampling rate. After optical modulation, all channels are multiplexed together and sent over 12 spans of 80 km fiber. On the receiver side, channels are de-multiplexed, filtered and demodulated using a coherent receiver and an 88 Gsa/s ADC. The NFT is calculated, remaining dispersion compensation is applied and the inverse Γ-transform is computed. Before symbol unmapping and BER calculation, a simple MMSE equalizer is applied. The fiber is modeled as having an attenuation of 0.2 dB/km, a mean dispersion β_2 of -21.68 $\times 10^{-27}$ s^2/m, a nonlinearity coefficient γ of 1.3 $W^{-1}km^{-1}$ and the EDFAs to have a noise figure of 5 dB.

3. Results and Discussion

Figure 4(a) shows the resulting BER for different spectral overlaps for 16- and 32-QAM transmission simulations of 8x25 GHz channels with a total of 800 subcarriers and a block length of 6 ns, resulting in an SE of 2.7 and 3.3 b/s/Hz, respectively. It reveals a clear performance gain when inter-channel spectral overlap is used. A small 1-GHz overlap already reduces the BER enough to achieve error-free transmission when using the 7% overhead hard decision forward error correction (HD-FEC) limit of 3.7×10^{-3} for 16-QAM or a 20% overhead soft decision (SD-)FEC limit of 2×10^{-2} for 32-QAM. This performance can be further improved by using neural network equalizers [3], dual polarization (double SE), probabilistic shaping [10], or joint modulation with the discrete part of the spectrum [8]. Excessively large overlaps result in the BER increasing again, as expected, considering that the spectral overlap together with the linear filtering violates the regularities of the NFT. This reduces performance, if applied at subcarriers where it is not needed. Figures 4(b) & 4(c) show the error vector magnitude (EVM) for a subset of subcarriers without and with spectral overlap, revealing an outstanding performance gain for the subcarriers located at the edges of the channels. This performance gain comes at the cost of a slight increase of the required electro-optical BW per channel.

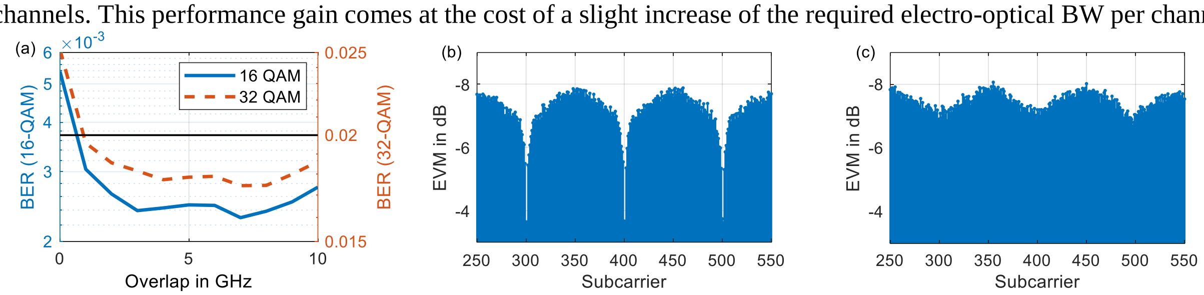

Fig. 4. (a) BER vs. spectral overlap for 16- and 32-QAM transmission with FEC-limits in black.
Subcarrier EVM for 32-QAM without (b) and with (c) 3-GHz overlap.

4. Conclusions

We have presented a new WDM NFDM transmitter concept that makes use of spectral overlap between adjacent channels to compensate the nonlinear inter-channel interaction. The proposed solution is highly scalable and does not require frequency guard bands. A scalable PIC architecture enabling this system has also been proposed.

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