Optical Mitigation of Interchannel Crosstalk for Multiple Spectrally Overlapped 20 Gbaud QPSK/16-QAM WDM Channels using Nonlinear Wave Mixing

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***Abstract*—Optical mitigation of interchannel interference (ICI) for multiple spectrally overlapped data channels is experimentally demonstrated without multichannel detection and channel spacing estimation. The ICI mitigation takes place in three stages of periodically poled lithium niobate (PPLN) waveguides. In the first PPLN stage, the conjugate copies of channels are generated; in the second stage, the overlapped signals are coherently multiplexed with different complex taps. In the third stage, the concurrent nonlinear processes and the coherent multiplexing of the signals with their delayed copies compensate the ICI. The bit error rate (BER) and the constellation diagrams of wavelength division multiplexed (WDM) channels carrying quadrature phase shift keying (QPSK) or 16 quadrature amplitude modulation (16-QAM) formats demonstrate the potential capability of the proposed method to reduce the ICI and its possible modulation format transparency. The effect of channel spacing on the performance of the method is also demonstrated. After optical ICI mitigation, a reduction of almost 4 dB is achieved for the value of signal-to-noise ratio (OSNR) at BER of 10^{-3} for 20 Gbaud QPSK signals with a channel spacing of 17.5 GHz. The overlapped WDM system of 20 Gbaud 16-QAM signals with channel spacing of 17.5 GHz is also ICI mitigated and error vector magnitudes (EVMs) are reduced by almost 28%.**

***Index Terms*—Interchannel interference, crosstalk, wavelength division multiplexing, nonlinear wave mixing, sum frequency generation, difference frequency generation, quadrature phase shift keying, quadrature amplitude modulation, periodically poled lithium niobate waveguides.**

I. INTRODUCTION

Maximizing spectral efficiency, defined in terms of bits/sec/Hz being transmitted within an available wavelength range of optical communication bandwidth, is a significant yet challenging task [1,2]. Approaches to increase spectral efficiency include; (i) reducing the guard band between adjacent data channels and (ii) spectrally overlapping of the data channels [3,4]. However, these methods typically give rise to increased interchannel interference (ICI), thereby requiring effective compensation techniques to recover data.

There have been reports of different approaches to reduce ICI in spectrally overlapped wavelength division multiplexed (WDM) systems using electronic digital signal processing (DSP) [5-12]. Typical DSP schemes for ICI reduction include the individual detection of each wavelength channel across a WDM system [13-15]. Common digital multichannel ICI compensation algorithms use the received crosstalk information to estimate the channel spacing and reduce the crosstalk of each channel [8-11]. The physical implementation of the DSP algorithm for ICI compensation usually requires a complex detection scheme that relies on multiple synchronized receivers or a single receiver with high bandwidth [16, 17].

Alternatively, interchannel crosstalk can be mitigated prior to detection using optical techniques, in which multichannel detection and channel spacing estimation are not necessarily required for ICI compensation of a single target channel [18,

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19]. In [18], an optical approach based on optical multicasting, complex tailoring, and multiplexing for ICI mitigation of overlapped channels of data carrying quadrature-phase-shift-keyed (QPSK) modulation is introduced and its potential for adding and dropping optical QPSK channels is explored. In [19], a system of overlapped channels carrying QPSK and quadrature amplitude modulation (QAM) is optically ICI compensated, and the ability of a scheme for ICI compensation of a hybrid overlapped system with channels carrying different modulation formats is demonstrated. This paper considers ways to further extend the approach of optical ICI compensation such that multiple spectrally overlapped WDM channels can be recovered simultaneously.

In this paper, we optically mitigate [20] the interchannel crosstalk of multiple spectrally overlapped channels of a WDM system within an individual element operating on multiple channels simultaneously. The ICI mitigation takes place in three stages of periodically poled lithium niobate (PPLN) waveguides. In the first stage, the optical conjugates of the WDM channels are constructed using a set of concurrent nonlinear processes. The conjugate copies of the signals are separated into two groups of even and odd channels. The amplitudes and phases of each channel in each group are adjusted and coherently mixed with their adjacent crosstalk channels in the second-stage PPLN to mitigate the ICIs. The conjugate copies are delayed, and in a third stage PPLN, these copies are mixed with the crosstalk signals to further decrease the ICI level. We experimentally demonstrate the proposed scheme using seven spectrally overlapped 20 Gbaud QPSK or 16-QAM channels. A nearly 4-dB OSNR gain is achieved for QPSK data channels at a BER of 10^{-3}. For the 16-QAM channels the error vector magnitudes (EVMs) are reduced by almost 28% for a channel spacing of 17.5 GHz.

II. Concept and Theory

Figure 1 shows the conceptual block diagram of the proposed optical ICI mitigation method for multiple spectrally overlapped channels. As depicted in Fig. 1, the incoming overlapped WDM channels are injected into a PPLN waveguide (PPLN-1) which is pumped by a CW laser at the quasi-phase matching (QPM) wavelength [21]. Inside PPLN-1, through concurrent sum frequency generation (SFG) and difference frequency generation (DFG), the WDM channels is wavelength-converted. That is, the conjugate copies of the WDM channels at the symmetrical spectral location with respect to QPM wavelength is generated. This is depicted in "conjugate copies generation in PPLN-1" block of the scheme in Fig. 1.

After conjugate copies generation block, the signals are sent to a two-output-port optical programmable filter based on liquid crystal on silicon (LCoS) technology. Odd and even channels are separated at the outputs of the LCoS filter and directed to different paths. In the path following port 1 of LCoS filter, the ICI of even channels is mitigated and in the path after port 2 of LCoS filter, the ICI mitigation of odd channels is performed. In the following, we only explain the ICI mitigation for even channels. Similar explanation is true for the ICI mitigation of the odd channels, if the terms "odd" and "even" are exchanged.

At port 1 of the LCoS filter, even channels of the initial signal and odd channels of the conjugate copied signal are passed. Simultaneously, the amplitudes and phases of the conjugate copies of odd channels are adjusted such that crosstalk suppression to be performed in the next stage is maximized. Next stage is composed of another PPLN

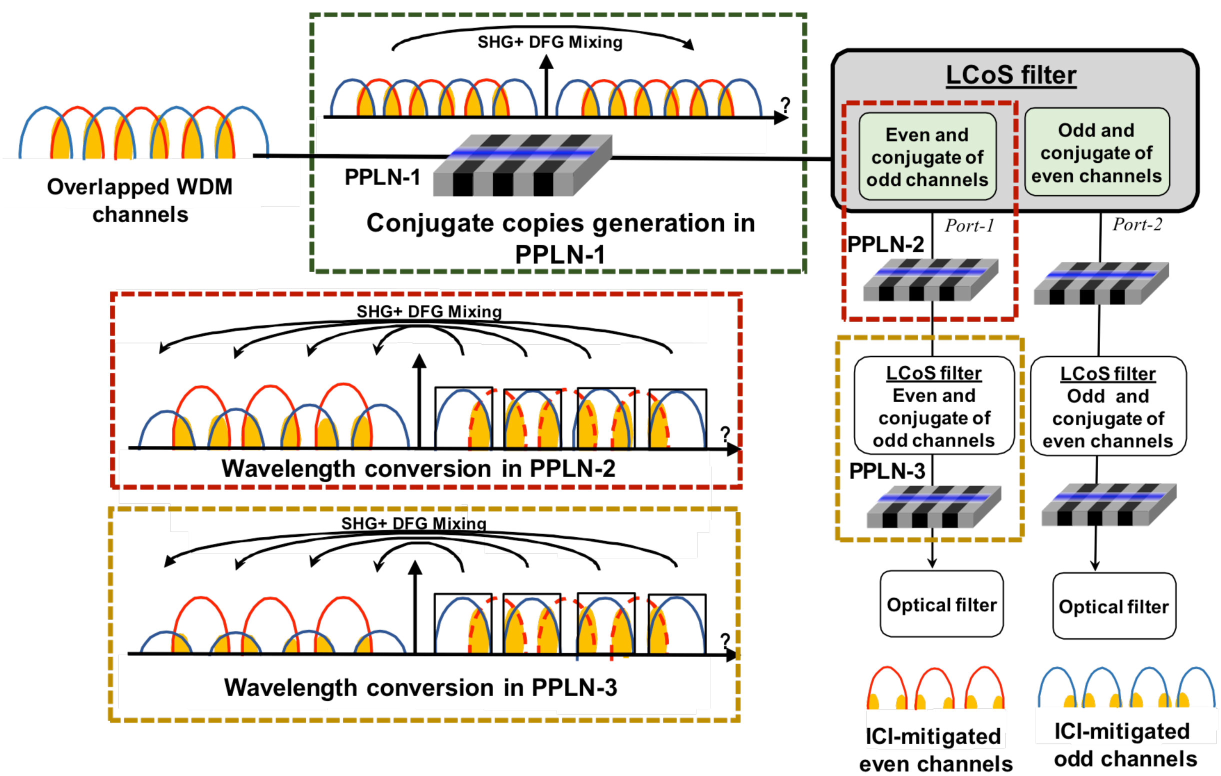

Fig. 1. Conceptual block diagram of optical interchannel crosstalk mitigation method. The scheme consists of three main blocks: (i) Conjugate copies generation in PPLN-1 waveguide, (ii) Wavelength conversion in PPLN-2 which coherently mixes original channels with amplitude/phase adjusted conjugate copies (iii) Wavelength conversion in PPLN-3 which coherently mixes original channels with amplitude/phase and delay adjusted conjugate copies.

waveguide (PPLN-2), in which through the wavelength conversion, the original even channels and the twice-wavelength-converted odd channels are coherently added.

Next, through another LCoS filter, even channels in the original wavelength region and the odd channels of conjugate copies are selected. The amplitudes, phases and delays of the conjugate copies are adjusted into the LCoS filter to further mitigate the ICI of even channels, through the wavelength conversion in the third PPLN (PPLN-3) [19].

Since the input WDM channels, the pump, and the conjugate copies remain throughout the wavelength conversion processes, there is no need to precisely adjust the frequency spacing among channels, and coherent addition of the input signal and the wavelength converted signal becomes possible. Also, we should mention that, we have used PPLN in our experiments for three main reasons: First because of the small size of the PPLN, there would be low latency or walk-off for the propagating signals compared to highly nonlinear fibers (HNLFs). Second, high conversion efficiency of PPLN potentially provides efficient nonlinear mixing of the signals. Third, since PPLN has a $\chi^{(2)}$-type nonlinear response, the possible nonlinear mixing processes are second harmonic generation (SHG), SFG and DFG which were used in our scheme. In an $\chi^{(3)}$ medium such as an HNLF, more undesirable mixing terms are produced. Therefore, PPLNs can be potentially used for the ICI mitigation of WDM channels with less crosstalk terms.

The mathematical representation of the proposed scheme is as follows. Consider three adjacent signals; S_{i-1}, S_i, and S_{i+1}. Waveform Y represents the spectral combination of these three signals with a channel spacing of Δf and is defined as follows:

$$Y(f) = S_{i-1}(f - \Delta f\,) + S_i(f) + S_{i+1}(f + \Delta f\,) \qquad (1)$$

Without loss of generality, we assume that i is an even number. In this case i–1 and i+1 are odd and the first and third terms in the right side of eq. 1 are interference terms. In PPLN-1, waveform Y^* is produced at symmetrical wavelength position with respect to the CW pump as schematically plotted in the "conjugate copy generation" block of Fig.1. Note that "*" denotes the complex conjugate. The two-output LCoS filter in the "Wavelength conversion in PPLN-2" block selects S_i, S_{i-1}* and S_{i+1}*. The amplitudes and phases of S_{i-1}* and S_{i+1}* are adjusted through complex taps; c_{i-1} and c_{i+1} imposed by LCoS filter. The signals at port 1, compose the adjusted signals X_{i-1} and X_{i+1} and Y_i as follows:

$$Y_i(f) \propto \alpha_i(f)S_{i-1}(f - \Delta f) + S_i(f) + \alpha_i(f)S_{i+1}(f + \Delta f\,) \quad (2)$$

$$X_{i-1}(f) \propto c_{i-1}S_{i-1}^*(f - \Delta f) + c_{i-1}\alpha_{i-1}^*(f)S_i^*(f) \qquad (3)$$

$$X_{i+1}(f) \propto c_{i+1}\alpha_{i+1}^*(f)S_i^*(f) + c_{i+1}S_{i+1}^*(f + \Delta f) \qquad (4)$$

In equations (2-4), $\alpha_j^*(f)$, (j = i–1, i+1) denotes the filtering response of the optical programmable filter, centered at the central frequency of the signal S_j^*. Also, $\alpha_i(f)$ represents the filtering response of the optical programmable filter, centered at the signal S_i. Since the channels are overlapped, the filtering responses affect the neighboring channels. Inside the "Wavelength conversion in PPLN-2" block, signal Y_i is mixed with signals X_{i-1}^* and X_{i+1}^*. The following terms will be obtained:

$$\tilde{Y}(f) = \gamma_{i-1}S_{i-1}(f - \Delta f) + \gamma_i S_i(f) + \gamma_{i+1}S_{i+1}(f + \Delta f) \qquad (5)$$

In eq. 5, $\gamma_{i-1}(f) = \alpha_i(f) + c_{i-1}^*$, $\gamma_i(f) = 1 + c_{i-1}^*\alpha_{i-1}(f) + c_{i+1}^*\alpha_{i+1}(f)$ and $\gamma_{i+1}(f) = a_i(f) + c_{i+1}^*$. The goal is to reduce the value of the crosstalk terms S_{i-1} and S_{i+1} through adjusting the coefficients, c_{i-1} and c_{i+1}. It should be noted that if the crosstalk terms are cancelled out completely, the tails of the main signal to survive would also be suppressed. Therefore, c_{i-1} and c_{i+1} are adjusted to minimize the coefficients of the crosstalk terms S_{i-1} and S_{i+1} and maximize the coefficient of S_i. Also, eq. 5 is similar to equations derived in [18] and will reduce to those equations if only one crosstalk term is considered.

Furthermore, as demonstrated in the schematic spectrum inside the "Wavelength conversion in PPLN-3" block of Fig. 1, signals $\gamma_{i-1}^*S_{i-1}^*$ and $\gamma_{i+1}^*S_{i+1}^*$ are selected at the output of the second LCoS filter inside the block. The amplitudes and phases of $\gamma_{i-1}^*S_{i-1}^*$ and $\gamma_{i+1}^*S_{i+1}^*$ are adjusted with complex taps c'_{i-1} and c'_{i+1}. Relative delays; τ_{i-1} and τ_{i+1}, are also imposed on $\gamma_{i-1}^*S_{i-1}^*$ and $\gamma_{i+1}^*S_{i+1}^*$ by the LCoS filter. The adjusted signals are then described by:

$$X_{i-1}{}'(f) \propto c_{i-1}{}'e^{j2\pi f\tau_{i-1}}\gamma_{i-1}{}^*S_{i-1}^*(f - \Delta f) + c_{i-1}{}'e^{j2\pi f\tau_{i-1}}\gamma_{i-1}{}^*(f)\alpha_{i-1}(f)S_i^*(f) \qquad (6)$$

$$X_{i+1}{}'(f) \propto c_{i+1}{}'e^{j2\pi f\tau_{i+1}}\gamma_{i+1}{}^*S_{i+1}^*(f + \Delta f) + c_{i+1}{}'e^{j2\pi f\tau_{i+1}}\gamma_{i+1}{}^*(f)\alpha_{i+1}(f)S_i^*(f) \qquad (7)$$

In the PPLN-3, $\tilde{Y}(f)$ is coherently mixed with signals $X_{i+1}{}'^*$ and $X_{i-1}{}'^*$. The resulting spectrum in the original spectral region as schematically depicted in "Wavelength conversion in PPLN-3" block of Fig. 1, would be:

$$\Psi(f) = \beta_{i-1}\gamma_{i-1}S_{i-1}(f - \Delta f) + \beta_i(f)\gamma_i(f)S_i(f) + \beta_{i+1}\gamma_{i+1}S_{i+1}(f + \Delta f) \qquad (8)$$

In which, $\beta_{i-1} = 1 + c'^{\,*}_{i-1}e^{-j2 f\tau_{i-1}}$, $\beta_i(f) = 1 + c'^{\,*}_{i-1}e^{-j2 f\tau_{i-1}}\alpha_{i-1}^*(f) + c'^{\,*}_{i+1}e^{-j2 f\tau_{i+1}}\alpha_{i+1}^*(f)$ and $\beta_{i+1} = 1 + c'^{\,*}_{i+1}e^{-j2 f\tau_{i+1}}$. To mitigate the ICIs on channel S_i, the values of c_j, c_j', and τ_j (j = i–1 or i+1) should be adjusted to have $\beta_{i-1}\gamma_{i-1}$ and $\beta_{i+1}\gamma_{i+1}$ relatively smaller compared to the coefficient of S_i, that is, $\beta_i(f)\gamma_i(f)$. In this case, the spectrum $\Psi(f)$ yields the ICI mitigation of channel Si. Similar to [11, 15, 18], the non-deterministic nature of signals due to the data and noise has not taken into account in the derivation of the above equations. Note that, the optical signal to noise ratio of the channels can be decreased by propagating through optical devices and nonlinear elements. However, the focus of this paper is on the scenarios for which the main cause of signal distortion is the ICI of neighboring channels. An overall improvement in signal

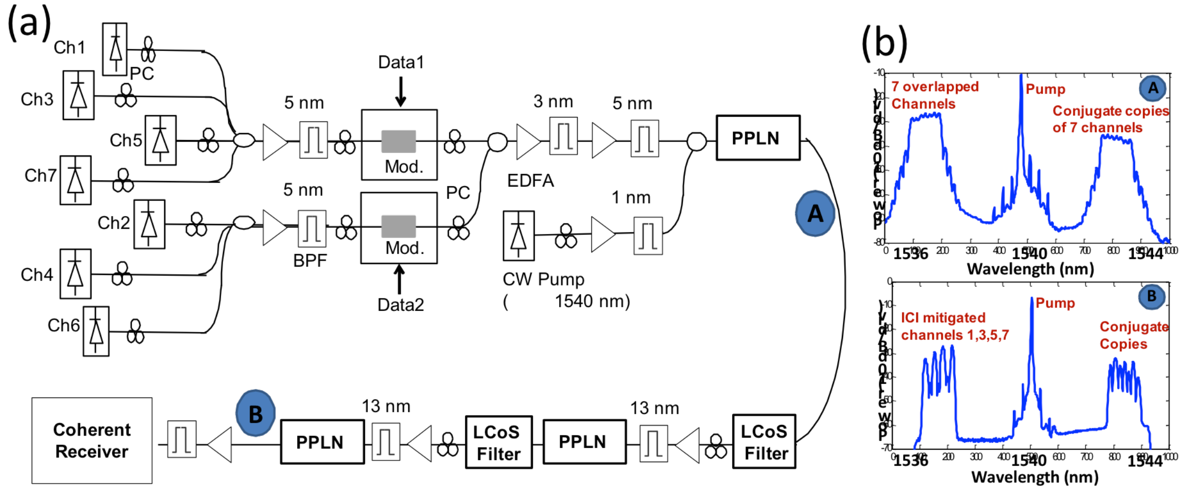

Fig. 2. (a) Experimental setup. PPLN: periodically poled lithium niobate, PC: polarization controller, LCoS: liquid crystal on silicon. (b) Optical spectrum of generated signal conjugate copies for 20 Gbaud overlapped QPSK channels at point A and optical spectrum of ICI mitigated odd channels 1, 3, 5, and 7 after the last PPLN waveguide at point B.

quality is obtained by the mitigation of those ICIs through the proposed scheme.

III. Experimental Setup for ICI Compensation of WDM Systems

Figure 2 shows the experimental setup to demonstrate the proof of concept for the proposed optical ICI mitigation scheme. Seven tunable narrow-linewidth laser sources are clustered in two groups to emulate the odd and even channels. The even and odd channels are created by two I/Q modulators with independent data streams. A pseudo-random bit pattern (PRBS) generator with pattern length of 2^{15}-1 and not-return-to-zero (NRZ) pulses are used to generate the data streams. To overlap the WDM channels, the optical frequencies of these seven channels are chosen so that their difference, Δf, is smaller than the baud rate of the data. The polarization of each signal channel is independently tuned to be aligned with the principal axis of the MZM modulator. The odd and even channels are combined using a 50/50 coupler. Optical signals are amplified using two stages of erbium-doped fiber amplifiers (EDFAs) and mixed with a CW pump laser at ~1540 nm. Before being combined, the CW pump laser is amplified to ~22 dBm using an EDFA followed by a tunable 1 *nm* filter. The optical signals and the CW pump are sent into the first PPLN waveguide to generate the conjugate copies of the signals. The QPM wavelength of the PPLN waveguide is temperature tuned and stabilized around the CW pump wavelength. This allows for the maximum conversion efficiency of the SHG and DFG processes inside the PPLN. In Fig. 2, the spectrum at point A shows the seven original channels, their generated conjugate copies, and the CW pump.

The signals, the conjugate copies, and the pump are sent to a two-output ports spatial light modulator (SLM) filter based on LCoS technology, in which the odd and even conjugate copies based on target channel selections for ICI mitigation of either odd or even channels are selected, and the amplitudes and phases of the signals and the conjugates are adjusted. Note that to mitigate the ICIs of even (odd) channels, the odd (even) signals from the generated conjugate copies and the original even (odd) channels are selected. The adjusted signals, the conjugates, and the CW pump are amplified to ~21 dBm and sent into a second PPLN waveguide with a similar QPM wavelength as the first PPLN waveguide. In this second waveguide, the signals are mixed with amplitude- and phase-adjusted crosstalk channels to reduce the ICIs. By using

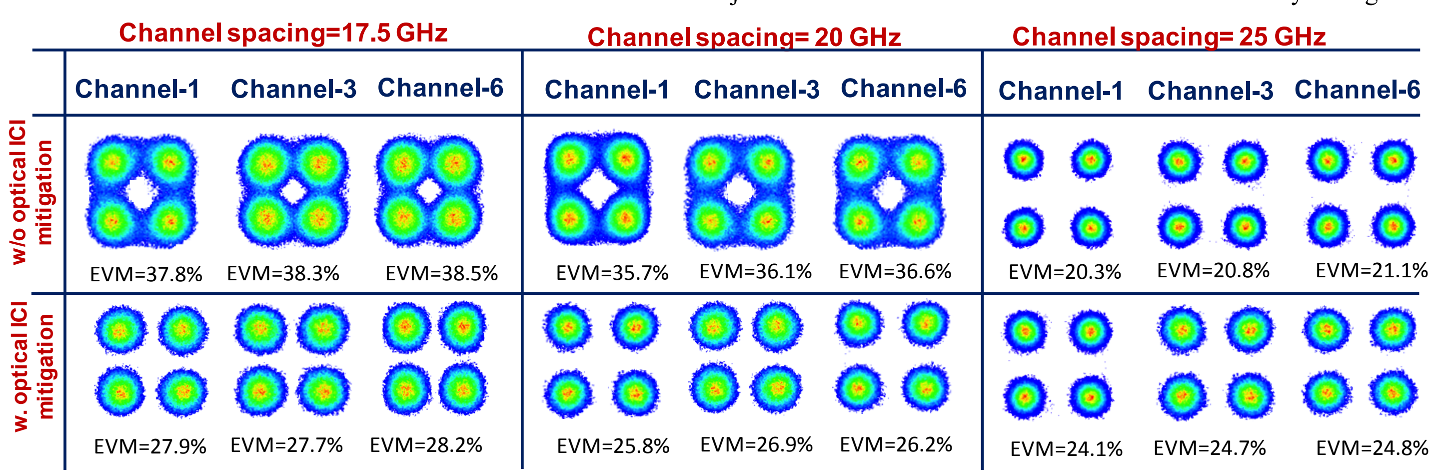

Fig. 3 Experimentally recorded signal constellation diagrams of channels 1, 3, and 6 with (w.) and without (w/o) optical ICI mitigation method for 20 Gbaud overlapped QPSK signals and at channel spacings of 17.5 GHz, 20 GHz, and 25 GHz.

another LCoS filter, the conjugate copies' amplitudes and phases are adjusted. In this second filter, the conjugate copies are further delayed and sent to another PPLN waveguide along the original target channels for ICI mitigation. Inside this PPLN waveguide, the signals and delayed variants of the crosstalk neighboring signals are mixed to further mitigate the ICIs. In each of these steps, it is not necessary to estimate the channel spacing because the pump and signals are preserved throughout the nonlinear processes. Channel spacing remains unchanged throughout each nonlinear interaction. The ICI mitigated channels are filtered and sent into a coherent detector to record the constellation diagrams and measure the BER. For offline DSP, we have used frequency offset and phase noise compensation. We avoided using adaptive equalization in DSP algorithms to be able to observe the performance of the proposed scheme for optical ICI mitigation.

IV. Results and Discussion

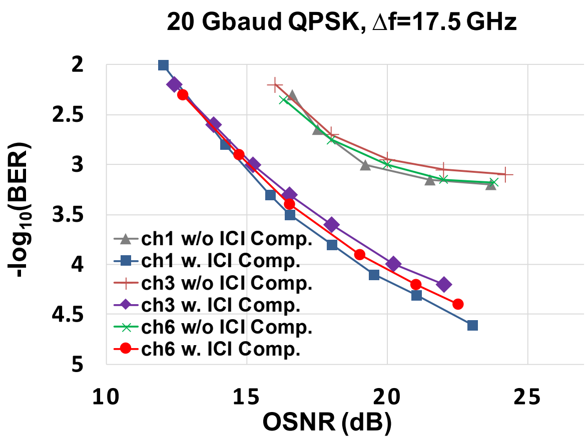

Fig. 4. BER measurements with (w.) and without (w/o) optical ICI compensation method for QPSK overlapped channels and for Δf =17.5 GHz

The seven lasers of the previous experimental setup are first modulated by two independent electrical QPSK data streams. Figure 3 shows the constellation diagrams of channels 1, 3, and 6. The constellations are measured (i) without optical ICI mitigation (back to back) and (ii) with optical ICI mitigation. To achieve the constellation diagrams for the ICI-mitigated signals the coefficients c_i and c_i' and delays are manually tuned by monitoring the received error vector magnitude (EVM).

The channels are modulated with 20 Gbaud signals, and experiments are run for three different values for channel spacing: 17.5 GHz, 20 GHz, and 25 GHz. The ICI mitigation method provides negligible benefit when the channel spacing is larger than the baud rate of the signals, which is acceptable because the ICI effect there is insignificant (Δf=25 GHz in Fig. 3). When the channel spacing is equal to or less than the signal baud rate, the ICI is significant, and the ICI mitigation on the proposed method becomes noticeable (Δf=20 GHz and 17.5 GHz in Fig. 3).

For all three channel spacings, the ICI mitigations for the odd channel (channel 3) shows similar performance as for the even channel (channel 6). Note that both channels 3 and 6 incur two crosstalk terms from two neighboring channels. The slightly lower EVMs for channel 1, which incurs just one interference term, can be attributed to lower power of this channel as demonstrated in the spectrum of Fig. 2(b).

Figure 4 shows the BER versus optical signal-to-noise ratio (OSNR) results for channels 1, 3, and 6 carrying 20 Gbaud QPSK signals and with the channel spacing of 17.5 GHz. For a QPSK channel with channel spacing of 17.5 GHz, the required OSNR to achieve a BER of 10^{-3} is reduced by ~4 dB after optical ICI mitigation.

To further investigate the performance of the proposed ICI mitigation scheme for WDM channels, a different format of the modulation is considered. The set of even and odd channels are now modulated with 16-QAM data. Figure 5 shows the constellation diagrams of channels 1, 3, and 6 with

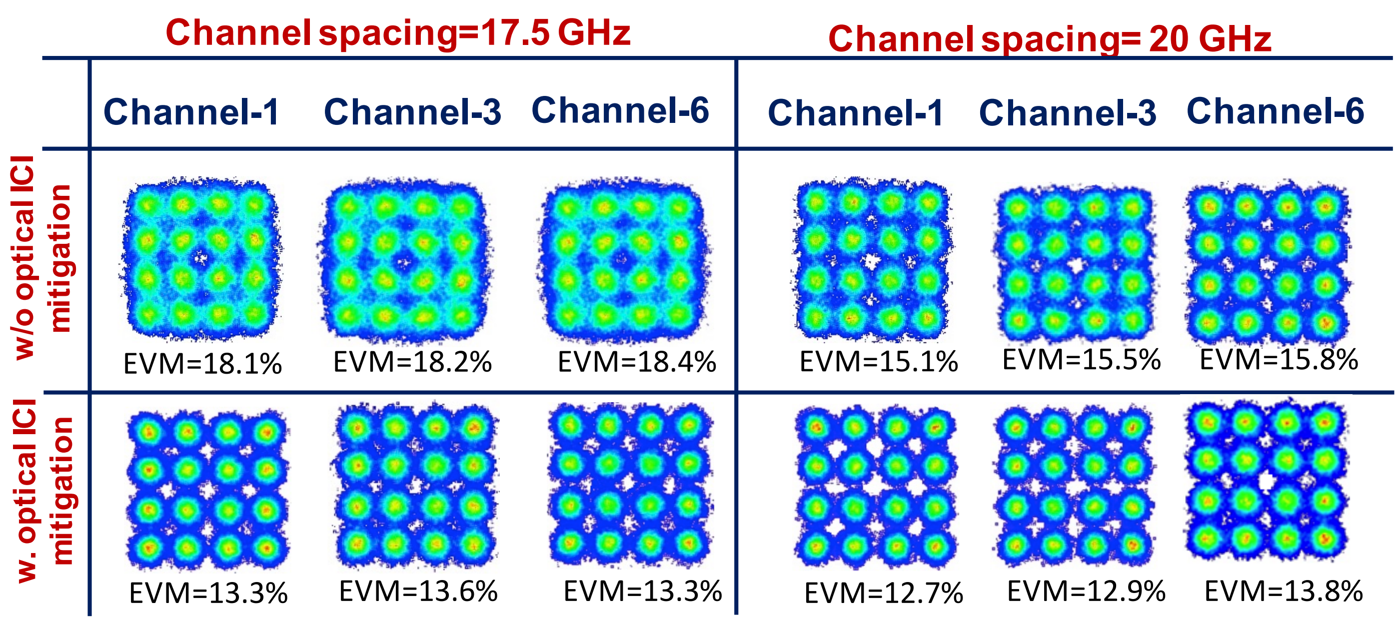

Fig. 5. Experimentally recorded signal constellation diagrams of channels 1, 3, and 6 with (w.) and without (w/o) optical ICI mitigation method for 20 Gbaud overlapped 16-QAM signals and at different channel spacings of 17.5 GHz and 20 GHz.

and without the optical ICI mitigation method under channel spacings of 17.5 GHz and 20 GHz. The constellation diagrams for a channel spacing of 25 GHz are not shown here because the ICI mitigation is again insignificant for a Δf larger than baud rate. Like QPSK constellation diagrams of the overlapped channels, the EVMs for 16-QAM signals are also generally reduced which shows possible modulation transparency of the proposed ICI mitigation scheme. The EVMs for all 16-QAM channels of the WDM system with channel spacing of 17.5 GHz are reduced by almost 28%. Fig. 6 shows the BER results of channels 1, 3, and 6. In this case, the channel spacing is 17.5 GHz. The 16-QAM channels are much more prone to the destructive effect of ICI than are the QPSK channels. Therefore, the BER versus OSNR curves of the QAM signals without ICI compensation fail to retain their linear trends, for a BER value around $10^{-2.5}$ and up. Again, a similar performance for ICI mitigation of odd and even channels is observed.

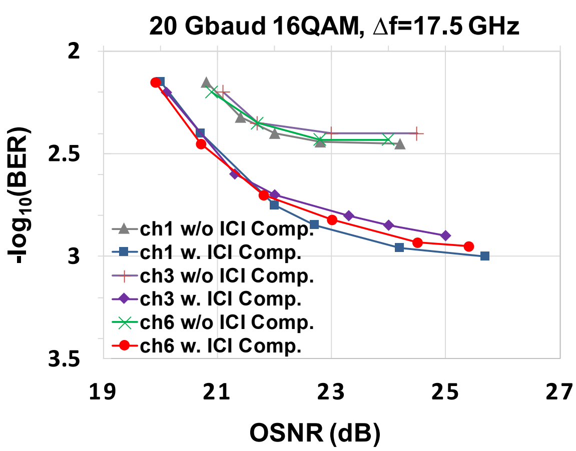

Fig. 6. BER measurements with (w.) and without (w/o) optical ICI compensation method for 20 Gbaud 16-QAM overlapped channels and for Δf =17.5 GHz.

V. Conclusion

A method for optical mitigation of the ICI of multiple spectrally overlapped data channels is experimentally demonstrated. The method is based on a cascade of conjugate wave generations along with phase, amplitude, and delay adjustments. For ICI mitigation using this method, individual detection and channel spacing estimation is not required, and the ICI of all channels can be mitigated simultaneously. The system performance is assessed for multiple spectrally overlapped 20 Gbaud QPSK and 16-QAM data channels. The similar performance of the method for both QPSK and 16-QAM channels shows the potential modulation transparency of the scheme. The BERs are measured for 20 Gbaud signals and under different channel overlapping (spacing) conditions inducing different ICIs. After optical ICI mitigation, a reduction of almost 4 dB is obtained in the required OSNR to achieve a BER of 10^{-3} for 20 Gbaud QPSK signals with a channel spacing of 17.5 GHz. The optical ICI compensation scheme has also been used for an overlapped WDM system of a 20 Gbaud 16-QAM signals with channel spacings of 17.5 GHz and 20GHz. The EVMs for all 16-QAM channels of a WDM system with channel spacing of 17.5 GHz, are reduced by almost 28%.

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