Experimental Demonstration of Tunable Optical De-aggregation of Each of Multiple Wavelength 16-QAM Channels into Two 4-PAM Channels

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Abstract: We experimentally demonstrate tunable all-optical simultaneous de-aggregation of multiple wavelength 16-QAM channels into two 4-PAM channels using a single stage nonlinear element. Tunability of the proposed approach over modulation format and bitrate is shown by de-aggregation of multiple channels for 10/15-Gbaud QPSK signals into two BPSK signals.

OCIS codes: (060.2360) Fiber optics links and subsystems; (070.4340) Nonlinear optical signal processing

1. Introduction

Future all-optical networks may utilize the aggregation of multiple lower-rate data channels into a single higher-rate data channel at transparent switching and access nodes, and such aggregation has been experimentally demonstrated [1, 2]. The reverse is also true, in that optical de-aggregation of a single higher-data-rate channel into multiple lower-rate channels may also be valuable in all-optical networks. Both these functions: (i) would benefit from tunability, (ii) may avoid inefficient optical-to-electrical-optical conversion, and (iii) could enhance network flexibility, reconfigurability, and spectral efficiency.

Previous reports have experimentally shown optical de-aggregation of a single data channel into two lower-rate channels using a feedback loop to stabilize phase within the de-aggregator [3-6]. In [7], optical de-aggregation of quadrature-phase-shift-keying (QPSK) into two binary-phase-shift-keying (BPSK) data channels of lower capacity without the need for feedback-based phase stabilization is experimentally demonstrated. Although the demonstrated experimental de-aggregation [3-9] mostly focus on QPSK to BPSK de-multiplexing, 16-quadrature-amplitude-modulation (QAM) to 4-pulse-amplitude-modulation (PAM) is also performed by using a single pump and generating multi-stage wave-mixing based on nonlinearity [8].

In this paper, we experimentally demonstrate tunable optical de-aggregation of each of multiple wavelength 16-QAM channels into two 4-PAM channels by implementing the mapping process onto the constellation axes. We add signal and its conjugate to do mapping process. In order to do that, we send signal with two corresponding pumps into a single stage nonlinear element to generate both copy and conjugate copy simultaneously in the same frequency to perform addition. This procedure can be done for multiple signals simultaneously by locating them in multiple wavelength. In two channels, 40-Gbit/s 16-QAM signal with error vector magnitude (EVM) of 10.2% is de-aggregated to in-phase (I) and quadraturephase (Q) 4-PAM signals with EVM of ~12%.

2. Concept

The concept of multiple channel all optical de-aggregation using one nonlinear stage is shown in Fig.1. In order to

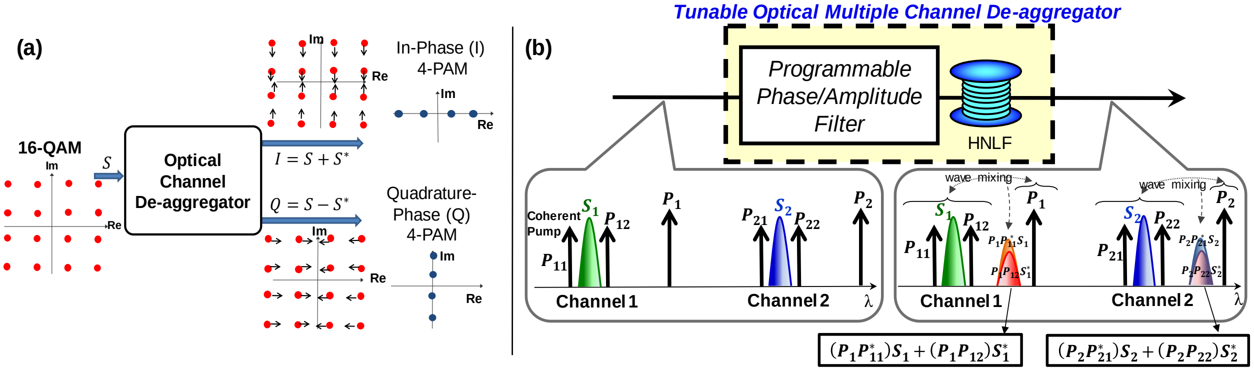

Fig. 1: Concept of optical channel de-aggregator, (a) optical mapping concept for modulation format conversion from 16-QAM to two 4-PAM (b) conceptual block diagram of multiple channel optical de-aggregation using single nonlinear stage.

perform de-aggregation of a 16-QAM, we can use the concept of constellation mapping into axes. As it is illustrated in Fig.1(a), by adding signal and its conjugate we can reach I-component of the signal, *i.e.*, I=S+S*. In this way, we map the 16-QAM constellation into I-axis which is a 4-PAM signal. Moreover, by changing plus sign to minus sign, meaning 180-degree phase shift in conjugate signal, the Q-component can be obtained, *i.e.*, Q=S-S*. This maps the constellation to the Q-axis. Fig.1(b) depicts the conceptual block diagram of multiple channel optical de-aggregation using mapping approach. The signal (S_1) which is surrounded by two in coherence pumps, plus another laser pump (P_1) are injected to a programmable phase/amplitude filter based on Liquid Crystal on Silicon (LCoS) technology. Second channel signal (S2) and pumps can be multiplexed to the fiber in the same fashion before the filter. It is possible to add more channels; however, here, we just consider two channels to show the concept. The signals are filtered and the desired phase/coefficients are induced. Signals and pumps are sent through a highly nonlinear fiber (HNLF) to generate copies and conjugate copies of the input signals in wave mixing processes. Please note that the copy and the conjugate copy of the signal are generated simultaneously in the same frequency meaning the addition of S and S* which is I-component. For example, in the first channel, signal S_1 mixes with pump P_1 through sum-frequency-generation (SFG) and then mixes with pump P_{11} through difference-frequency-generation (DFG) which leads to generation of the copy. Beside, P_1 mixes with P_{12} through SFG and then S_1 through DFG to generate the conjugate copy in the same frequency. This leads to addition of the signal and its conjugate which generates I-component. It is possible to shift phase by 180-degree using programmable phase/amplitude filter and perform subtraction to have Q-component in the output. The same process is performed for the second channel.

3. Experimental Setup

The experimental setup is depicted in Fig.2. We modulated two 1-kHz lasers at 1546.9 nm and 1556.9 nm with 2^{15}-1 PRBS data at 10/15 Gbaud by an arbitrary waveform generator (AWG). The I-component, at the output of AWG, is combined with sinusoidal tone generated by a 20 GHz frequency oscillator. The clocks of the AWG and the frequency oscillator are synchronized by a 10 MHz reference. The same data is modulated on two lasers for both data channels in a Mach-Zehnder modulator (MZM). Later on, a delay component is used to de-correlated data channels and make them independent at the receiver side. The signal is amplified and sent to the LCoS filter to separate two channels and adjust the power levels and relative phases for each channel signal and pumps. The optical spectrum of the signal and pumps in channel 1 is shown in Fig. 2(a). Then, channel 1 is amplified and combined in a 50/50 coupler with an amplified CW pump at 1547.9 nm (P_1). Similarly, channel 2 is amplified and combined in a 50/50 coupler with an amplified CW pump at 1558.9 nm (P_2). Two channels and pumps are again combined together in a polarization beam splitter (PBS) to be sent into a 450 m HNLF (ZDW=1556nm). The used lasers for signals and pumps are independent and each laser has wavelength stability of ± 50MHz over an hour. The HNLF output signal spectrum is shown in Fig. 2(b). A Band-pass filter (BPF) is used to select the de-aggregated signal of channel 1 or 2. Finally, the output is sent into an 80Gsample/s coherent receiver for analysis.

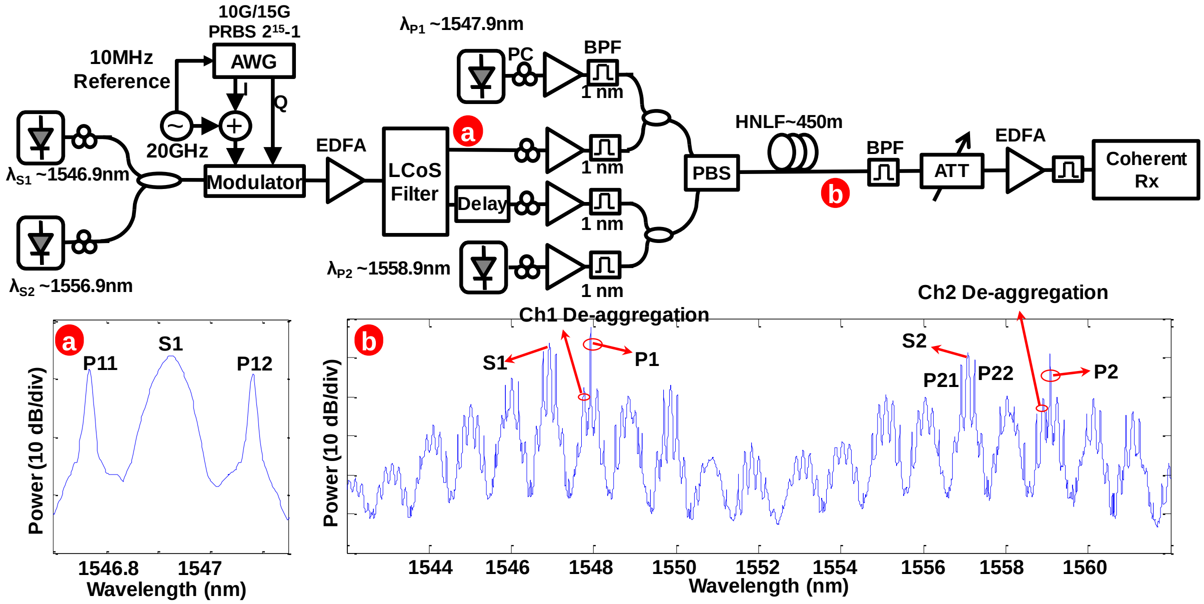

Fig. 2: Experimental setup and (a) Spectrum of first channel before nonlinear stage, (b) Spectrum after nonlinear stage. AWG: Arbitrary Waveform Generator, EDFA: Erbium-Doped Fiber Amplifier, LCoS: Liquid Crystal on Silicon, BPF: Band Pass Filter, PC: Polarization Controller, PBS: Polarization Beam Splitter, HNLF: Highly Non-Linear Fiber, ATT: attenuator

4. Results and discussion

Fig.3 shows constellation of QPSK and 16-QAM signal as the input and corresponding de-aggregated signal for both channels. In channel 1, a 40Gbit/s 16-QAM signal with EVM of ~10.2% is de-aggregated to two 20Gbit/s 4-PAM signals as I and Q-components with EVM of ~12% at the output. Almost the same result is observed for the second channel which de-multiplex a 40Gbit/s 16-QAM to two 20Gbit/s 4-PAM simultaneously. In order to identify tunability of the proposed setup over modulation format, we send 20Gbit/s QPSK signal with EVM of ~11.5% as the input in two channels. The QPSK signal is de-aggregated into two 10Gbit/s BPSK signals with EVM of ~15%. Again, almost similar results are achieved in both channels.

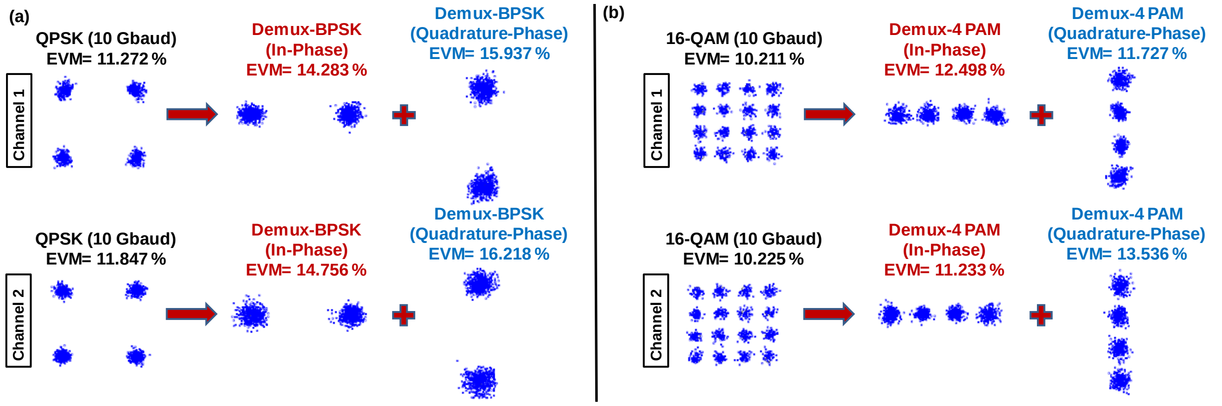

Fig. 3: Constellation before and after the de-aggregation for (a) QPSK, and (b) 16-QAM, in both channels.

Fig.4 shows bit error rate (BER) measurements for the input QPSK signal and output I and Q-component of de-aggregated BPSK signals versus OSNR for both channels. At BER of 1e-4, the OSNR difference between input QPSK signal and output BPSK signals is ~3dB which indicates good performance for de-aggregator. This performance is valid for both channels. Moreover, in order to show the baud rate tunability of the setup, we de-aggregated the QPSK signal at different baud rate of 15Gbuad. As it is illustrated in Fig.4(b), the performance is almost similar to 10 Gbaud case with less than 0.4 dB OSNR penalty. However, de-aggregation is done for both channels properly.

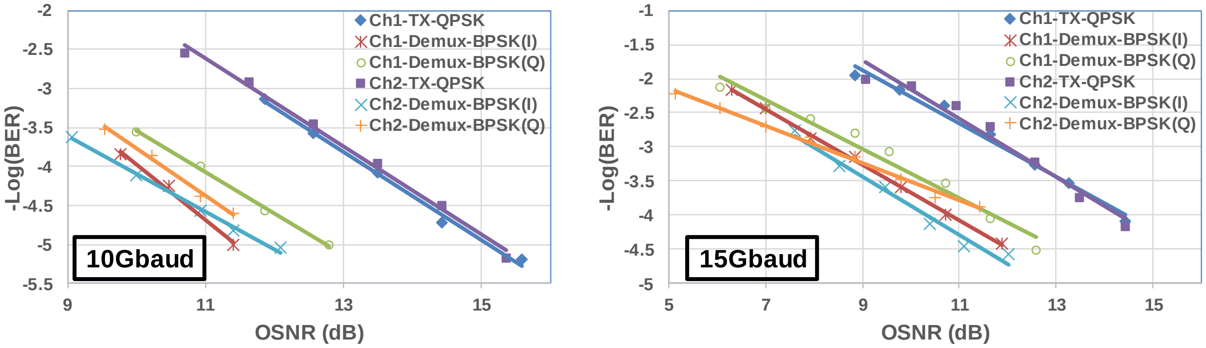

Fig. 4: BER performance before and after the multichannel de-aggregator system for (a) 10Gbaud and (b) 15Gbaud QPSK signal.

5. Acknowledgments

The authors would like to acknowledge the support of CIAN, Huawei/Futurewei, NIST and NSF.

6. References

[1] M. R. Chitgarha, et al, "Demonstration of reconfigurable optical generation of higher-order modulation formats up to 64 QAM using optical nonlinearity," Opt. letters 38.17 (2013).

[2] G.-W. Lu, et al, "Flexible high-order QAM transmitter using tandem IQ modulators for generating 16/32/36/64-QAM with balanced complexity in electronics and optics," Opt. Express 21, 6213-6223, (2013).

[3] F. Da Ros et al., "Simultaneous QPSK-to-2×BPSK Wavelength and Modulation Format Conversion in PPLN," IEEE PTL. 26, 1207 (2014).

[4] A. Lorences-Riesgo et al, "Experimental analysis of degenerate vector phase-sensitive amplification," Opt. Express, 22, 21889-21902 (2014).

[5] M. Gao et al, "Low-penalty phase de-multiplexing of QPSK signal by dual-pump phase sensitive amplifiers," ECOC, paper We.3.A.5. (2013).

[6] F. Parmigiani et al, "Polarization-assisted phase-sensitive processor," J. Lightwave Technol. 33, 1166-1174 (2015).

[7] M. Ziyadi et al., "Optical channel de-aggregation of quadraturephase- shift-keying and eight-phase-shift-keying data using mapping onto constellation axes," Opt. Letters, **40**(21), pp. 4899-4902 (2015).

[8] M. Ziyadi et al., "Tunable optical de-aggregation of a 40-Gbit/s 16-QAM signal into two 20-Gbit/s 4-PAM signals using a coherent frequency comb and nonlinear processing," CLEO, paper SM3F.5 (2016).