Experimental Generation of a 64-QAM by Optically Aggregating Three Independent QPSK Channels using Nonlinear Wave Mixing of Multiple Kerr Comb Lines

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Abstract: We experimentally demonstrate an arbitrary optical higher order QAM generation using single stage nonlinear element and Kerr frequency comb. We successfully generated 80-Gbit/s 16-QAM and 120Gbit/s 64-QAM at EVM of 6.5% and 5.5% by multiplexing two and three 40-Gbit/s QPSK signals, respectively.

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1. Introduction

There is interest in high-capacity optical communication systems to increase the spectral efficiency (i.e., bits/sec/Hz) of the generated data channels. One common approach is to have multi-level data encoding on both the amplitude and phase of the optical carrier wave, such as by quadrature-amplitude-modulation (QAM) [1,2]. Typically, QAM can be generated today by driving two Mach-Zehnder interferometers with multi-level voltage signals [3,4]. As the number of QAM levels and baud rate increase, the technical challenges in generating the data in this fashion can become more difficult, including: (i) generating a linear transfer function using Mach Zehnders for many input voltage levels, and (ii) generating a high-quality drive signal for high baud rates. Approaches that use optical nonlinear wave mixing may have a larger linear transfer function and a higher bandwidth capability [5].

Previously, optical nonlinear wave mixing of comb lines from a mode-locked laser was used to tunably generate a 64-QAM data channel by aggregating three quadrature-phase-shift-keyed (QPSK) channels [6]. In that approach, three waves are mixed onto a fourth wavelength, in which conversion efficiency becomes a key limitation. A potential valuable goal might be to perform the data optical aggregation but increase the efficiency of the process.

In this paper, we experimental generation of a 64-QAM 20-Gbaud data channel by optically aggregating three independent QPSK channels using nonlinear wave mixing of multiple Kerr comb lines. There have been a few reports using Kerr frequency comb for optical signal processing applications. Here, we use the coherency of the Kerr comb lines to generate higher order QAM signals. In order to generate 64-QAM, instead of copying three signals into fourth wavelength, we keep one signal and generate the copy of two others to the same frequency as the first signal. In this way we can save conversion efficiency power loss in compare with previous approach. Also, we do not need to add fourth pump to generate copy which in turn save power. Using this method 120 Gbit/s 64-QAM and 80 Gbit/s 16-QAM with EVM of 6.5% and 5.5% are generated.

2. Concept

The concept of principle operation of our proposed optical higher-order QAM generation is shown in Fig.1. As illustrated in Fig.1(a), in order to generate a 64-QAM signal, we can add coherently three QPSK signals with different complex coefficient which enables vector addition. Fig.1(b) depicts conceptual block diagram in which wave mixing in nonlinear element is illustrated for both old approach (approach 1) [6] and the new proposed

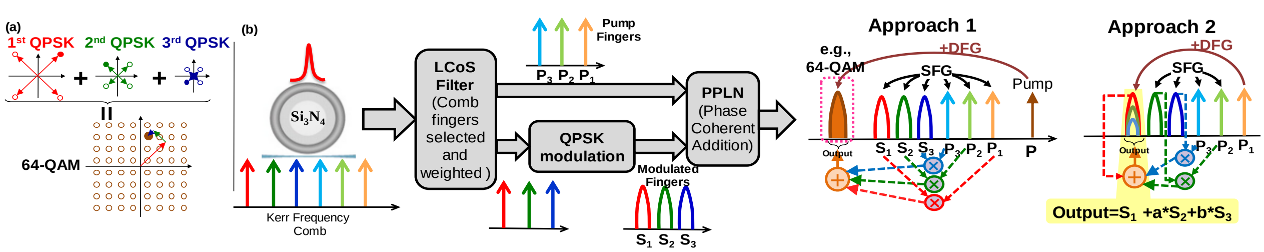

Fig. 1: Concept of optical modulation format multiplexing, (a) concept of generating 64-QAM using three QPSK signals through vector addition (b) conceptual block diagram of higher order modulation format generation with two approaches.

approach (approach 2). First, Kerr frequency comb is used to generate multiple frequency comb fingers at different wavelength which are coherent with each other. A liquid crystal on silicon (LCoS) programmable filter is used to select suitable fingers as pumps and signals and apply complex weights on the comb lines. At the output, there are two separate path for signals and pumps. In signal path, an optical modulator is used to modulate QPSK signal of the selected comb fingers. Then, signals and pumps merge together and send into periodically poled lithium niobate (PPLN) waveguide for nonlinear mixing in order to generate higher order QAM. In approach 1, we generate the copy of three signals in the fourth wavelength by exploiting sum frequency generation (SFG) and difference frequency generation (DFG) processes and adding fourth pump in PPLN. In approach 2, we keep one of the signals at the output as it is and generate the copy of the two other signals on the same frequency as the first signal. In this way, not only we avoid power loss due to conversion of one signal, but also the fourth pump is eliminated which leads to power saving for the rest of them.

3. Experimental Setup

The experimental setup is depicted in Fig.2. The frequency comb is generated in the silicon nitride microring resonator through parametric frequency conversion. An external cavity tunable diode laser (ECDL) is amplified by a high power C-band erbium doped fiber laser (EDFA). Then, the amplified continuous wave passes through filter, isolator and polarization controller to be coupled into the chip through a lensed fiber. Optical spectrum of the generated Kerr frequency comb is shown on Fig.2(a). The frequency spectrum range (FSR) of the generated comb is 191.8 GHz. We used six fingers around 1550 nm, Fig.2 (b). In order to boost their power, they are amplified using a low-noise EDFA and then sent to the LCoS filter. In order to generate 16-QAM from two QPSK signal, we choose six fingers in LCoS, three lines for signals and three lines as pumps. 20-Gbaud QPSK signals are modulated on the selected lines and the amplified in a low noise EDFA. The spectrum of it is illustrated in Fig.2(c). Afterward, signals and pumps passes through high power EDFAs and merge together to be sent into PPLN. A 400 m DCF is used to induce one symbol delay between signals. A Band-pass filter (BPF) is used to select the generated higher order signal and the output is sent into an 80Gsample/s coherent receiver for analysis.

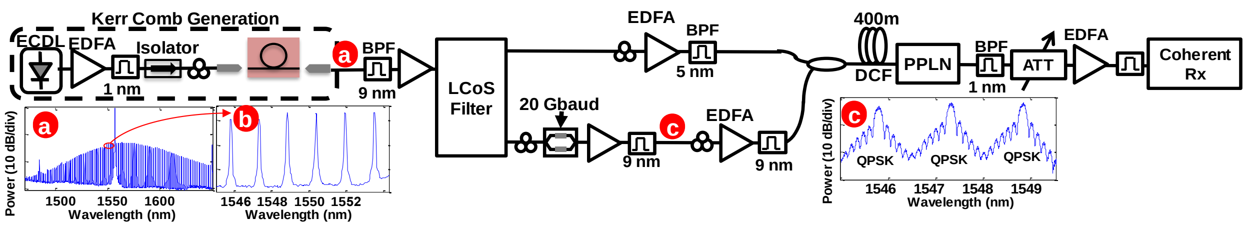

Fig. 2: Experimental setup and spectrum of (a) generated Kerr frequency comb, (b) zoom in target comb lines, (c) modulated signals.

4. Results and discussion

Fig.3 shows spectrums of PPLN output and constellation of the received signal in both approaches. In Fig. 3(a-d) generation of 64-QAM is illustrated. Fig. 3(c) shows the constellation of 64-QAM generated with approach 2, corresponding to spectrum on Fig. 3(a). Its EVM is 5.5% which is better than the result for approach 1, Fig. 3(b,d). By turning off one channel we can achieve 16-QAM as its results depicted in Fig. 4(e-h). EVM of generated 16-QAM in approach 1 is 8.7%, Fig. 3(f,h), whereas EVM of approach 2 is 6.5%, Fig. 3(e,g). Similarly, better result is achieved in approach 2 in compare with approach 1 because, as it can be seen from spectrums, we save more than 10 dB power in this approach.

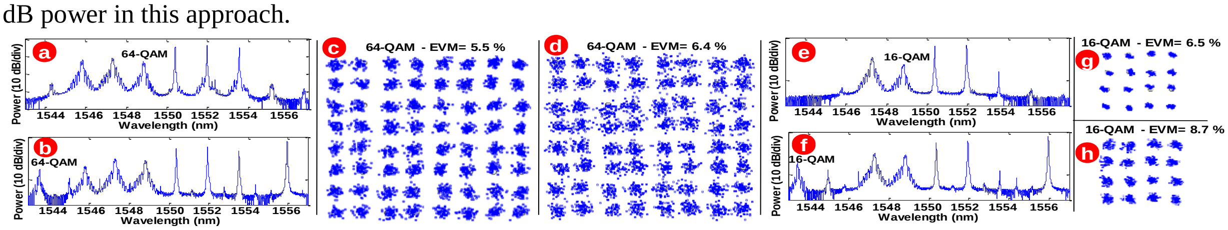

Fig. 3: Spectrums of PPLN output and constellations of received signal in both approaches. in both approaches.

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6. References

[1] G. Li, Adv. Opt. Photon. 1, 279 (2009).
[2] A. H. Gnauck, et al., J. Lightwave Tech., 30, 532 (2012).
[3] Y. Koizumi, et al., Opt. Express, 20, 12508 (2012).
[4] R. Schmogrow, et al., IEEE PTL, 22, 1601 (2010).
[5] G. Agrawal, *Nonlinear Fiber Optics* (Academic, 2001).
[6] S. Sternklar, et al., Opt. Letters, 39(16), 4915 (2014).