Demonstration of Tunable Optical Generation of Higher-Order Modulation Formats using Nonlinearities and Coherent Frequency Comb

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Abstract: We demonstrate the generation of optical 16-QAM and 64-QAM at EVM 6.8% and 6.4% respectively using nonlinearities and coherent frequency comb. We also demonstrated a successful transmission through 80-km SMF-28 after compensating with 20-km DCF with negligible penalty.
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OCIS codes: (060.2360) Fiber optics links and subsystems; (190.4223) Nonlinear wave mixing

1. Introduction

There has been significant interest in higher-order modulation formats for optical communication systems due to the higher spectral efficiency in terms of bit/s/Hz. Specifically, quadrature phase shift keying (QPSK) is an example of 4-ary phase encoding, whereas 16 quadrature amplitude modulation (QAM) is an example of 16-ary amplitude/phase encoding.[1,2] Moreover, QAM can go to higher orders, such as 64 and beyond.
A common technique for generating higher-order formats is to use electronic circuits to drive an I/Q modulator. However, key challenges for this approach are: (a) the limited linearity of the electronics at high baud rates, such that the spacing of the data constellation points on the I/Q plot will no longer be uniform, and (b) electronic approaches may become difficult at rates exceeding 100-Gbaud.
As an alternative, nonlinear optical processes hold the promise of high speed, format and phase transparency, low noise, and high linearity.[3]. As an example, an NOLM loop can be used to multiplexed 4 OOK signals into a 16-QAM[4]. These methods tend not to be transparent for phase modulation formats. We recently demonstrate a method to multiplex QPSK signals into a 64-QAM using 2 cascaded nonlinear stages [5]. In this method, however, two nonlinear stages degrade the quality of the generated QAM. A laudable goal would be to use fewer nonlinear stages for better efficiency and the potential to go to higher-order formats.
In this paper, we demonstrate a scheme for tunable optical generation of higher-order modulation formats using nonlinearities and coherent frequency comb. Due to the coherency of comb fingers, coherent multiplexing process can be done completely in one nonlinear stage. Optical 16-QAM and 64-QAM are generated at EVM 6.8% and 6.4% respectively. We also demonstrated a successful transmission through 80-km SMF-28 after compensating with 20-km DCF with negligible penalty.

2. Concept

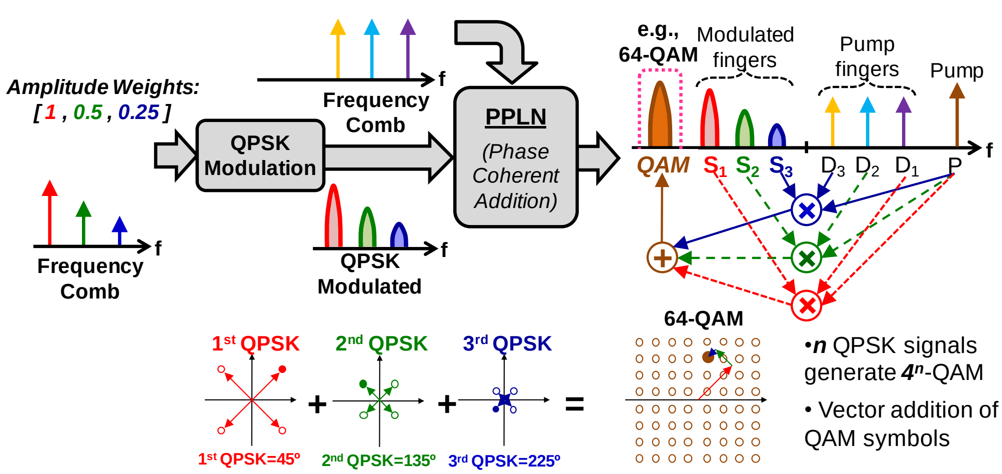

Fig. 1. Conceptual block diagram higher-order QAM generation

The conceptual block diagram of the tunable optical QAM transmitter is in Fig. 1. Multiple fingers from a coherent comb source are selected and modulated using an I/Q modulator with QPSK modulation format. These signals along with another set of coherent comb fingers with equal frequency spacing and a CW pump laser (E_{CW}) are injected into a periodically-poled-lithium-niobate (PPLN) waveguide to perform coherent addition of QSPK signals. This process can be done through two cascaded second order nonlinear wave mixings (sum frequency generation (SFG), difference frequency generation (DFG)). The multiplexed signal becomes proportional to $(E_{CW}(t))^{*}\Sigma\ E_{Pi}(t).E_{Si}(t)$. The amplitude and phase of comb fingers determine the coefficients of this coherent addition and thus, by varying these parameters, QAM with different constellation size and/or encoding can be generated.

3. Experimental Setup

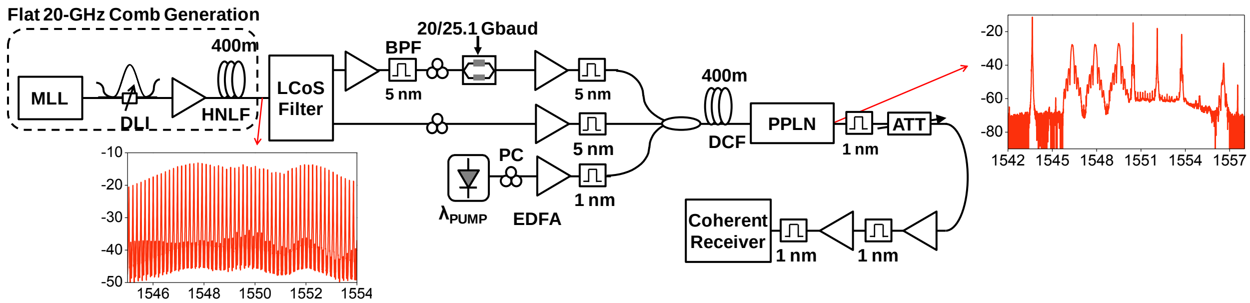

Fig. 1. Experimental setup of higher-order QAM generation.

The experimental setup for the tunable QAM encoder is shown in Fig. 2. A mode-locked laser with 10GHz repletion rate and 2-ps pulse width is used to generate a coherent comb with 10-GHz frequency spacing. This optical comb is passed through a DLI with FSR 20-GHz to increase the frequency spacing. The 20-GHz comb is then passed through an HNLF fiber to generate a flat and broad spectrum. A Liquid Crystal on Silicon (LCoS) filter can be utilized to select and write complex weights on comb fingers and separate them into signal path and pump path. A nested Mach-Zehnder modulator is used to generate the 20/25.1-Gbit/s BPSK/QPSK data (PRBS 2^{31}-1) on the signal path. These signals along with the comb fingers selected for pump path and a CW laser pump are sent to a PPLN (5-cm length) after enough amplification to perform coherent multiplexing of original signals. The multiplexed signal is then filtered and sent to the coherent receiver.

4. Results and Discussion

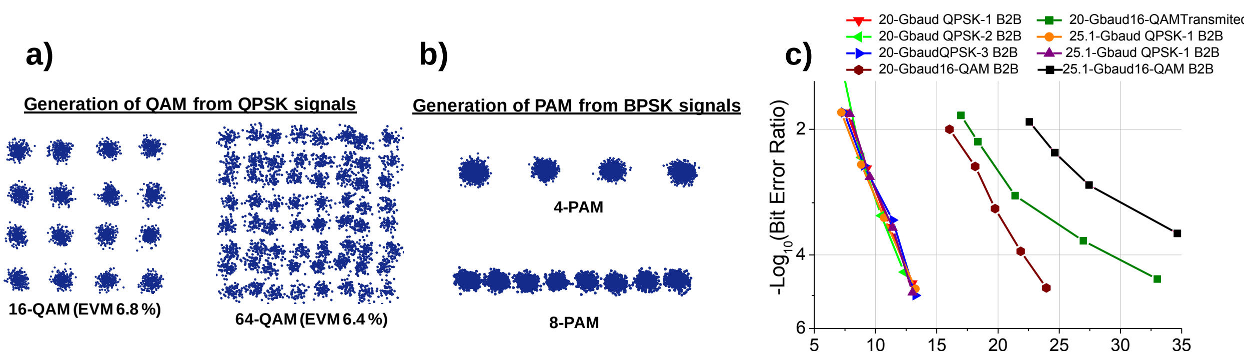

Fig. 3. (a) 16-, 64-QAM generation using 20-Gbaud QPSK, (b)4-, 8-PAM generation using 20-Gbaud BPSK (c) BER measurements

Fig.3(a) shows QAM generation using 20-Gbaud QPSK signals. By coherent multiplexing of two QPSK signals with appropriate weights, a 16-QAM with EVM 6.8% can be generated. 64-QAM constellation with EVM 6.4% is also shown in fig.3(a) which can be generated from three QPSK signals. If the original signals are two or three BPSK signals, a pulse-amplitude-modulation (PAM) signals with 4 and 8 points can be generated respectively (Fig. 3(b)). The performance of the higher-order QAM encoder is assessed using BER measurements. As it can be seen, a 16-QAM signal can be generated at both 20-Gbaud and 25.1-Gbaud. The 20-Gbaud 16-QAM is also transmitted through 80-km SMF-28 and 20-km DCF fiber with negligible power penalty.

Acknowledgements

We acknowledge the support of DARPA, Cisco, CIAN and NSF.

5. References

[1] Y. Koizumi, Optics Express, Vol. 20, Issue 11, pp. 12508-12514 (2012)
[2]D. J. Geisler, Opt. Express 19, 8242-8253 (2011)
[3] Agrawal, G. Nonlinear Fiber Optics (Academic Press, 2001)
[4] G. Huang, JLT, Vol. 30, Issue 9, pp. 1342-1350 (2012)
[5] M. R. Chitgarha, ECOC (2012)