Experimental Demonstration of a Novel All-Optical Multilevel 4-Amplitude-Shifted-Keying Coding/Decoding Scheme

Li Huo, Jian Zhao, Chinlon Lin, Chun-Kit Chan and Zhaoxin Wang
Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N. T., Hong Kong SAR, China.
Tel: +852-2609-8385, Fax: +852-2603-5032, Email:lihuo@ie.cuhk.edu.hk

Abstract: We demonstrated for the first time an all-optical multilevel 4-amplitude-shifted-keying coding and decoding technique, which encodes two on-off-keying signals into a 4-ASK signal using cross absorption modulation in an electro-absorption modulator and employs fiber-based all-optical approach to facilitate data detection.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Due to the ever-increasing demands for bandwidth, carriers need to upgrade their legacy systems to higher bit rates. Multilevel amplitude-shifted-keying (ASK) signaling such as 4-ASK is potentially an effective way to perform such upgrading. 4-ASK doubles the bit rate without expanding the spectral width. Consequently, it shows a similar tolerance to chromatic dispersion (CD) and polarization mode dispersion (PMD) to the installed system [1, 2]. The existing 4-ASK coding and decoding methods are in the electrical domain [1, 2]. However, it is more attractive to implement them in the optical domain. Optical fiber can connect two terminal equipments flexibly without the need to modify the circuit board inside of them. Basic supporting technologies of 4-ASK signal generation, such as power adjustment and data alignment, are more cost-effective and compact in optics. Moreover, all-optical 4-ASK can be used in future transparent all-optical network intermediate nodes as a form of contention solution to maximize the network capacity. In this paper, we demonstrated, for the first time, an all-optical 4-ASK coding and decoding technique. It is shown that such coding method can easily achieve arbitrary level spacing by tuning a variable ratio coupler and the bias voltage of the electro-absorption modulator (EAM). The highly nonlinear fiber (HNLF) with the subsequent narrowband filtering before the receiver can effectively enlarge the desired eye opening to facilitate the bit-error rate (BER) detection even when a conventional on-off-keying (OOK) receiver is employed.

2. Principles and Experimental Setup

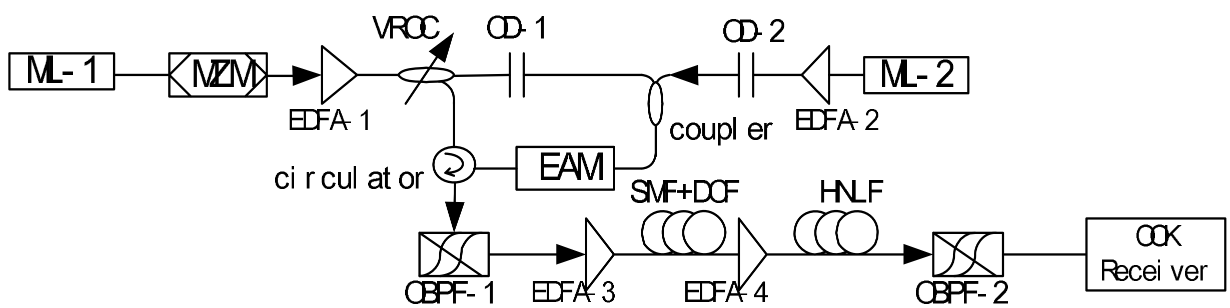

Fig. 1. Experimental Setup

Fig. 1 depicts the experimental setup. A 10GHz, 3ps pulse train with the wavelength centered at 1545 nm was generated by the mode-locked laser-1 (ML-1) and modulated by the Mach-Zender modulator (MZM). Then the signal was amplified using the erbium-doped fiber amplifier-1 (EDFA-1) and split by a variable ratio optical coupler (VROC) into two branches to emulate the two on-off-keying (OOK) input signals. The two signals were de-correlated and properly aligned by the optical delay-1 (OD-1) and launched into the -3V reverse biased EAM from the opposite directions to avoid the homodyne interference. The optical powers injected into the two sides of EAM were 13dBm and 10dBm, respectively. OD-1 was adjusted to make pulses from the opposite sides collide in the EAM. Because there were totally 4 in-chip optical power level combinations, a 4-level time window in EAM was created through cross absorption modulation (XAM). Therefore, when a second pulse train from the ML-2 at 1550 nm entered EAM, 4-level information was transcribed to the new wavelength and 4-ASK coding function was realized. The output power of EDFA-2 was 7dBm. The optical delay-2 (OD-2) was used to make the pulses peak in the middle of the time window of the EAM. The generated 4-ASK signal was filtered out from the circulator with a 2-nm optical bandpass filter-1 (OBPF-1) centered at 1550nm and amplified by the EDFA-3. The 4-ASK signal was transmitted along the 40-km single-mode-fiber and 8-km dispersion compensation fiber (DCF). At the receiver end, 4-ASK signal should be converted into three separated 2-level patterns for data reconstruction. In the experiment, it was found the capability of a conventional OOK receiver, which consists of a photodetector and an electrical limiting amplifier, to differentiate these levels was quite limited. In this paper, we found that such procedure could be implemented in the optical domain by using the highly nonlinear fiber (HNLF) with the subsequent optical filtering. After the amplification using the EDFA-4, a 2-km HNLF with the nonlinear coefficient of γ=10W/km^{-1} and zero dispersion of 1543 nm was employed to broaden the spectrum of the signal through the self-phase modulation effect. As the broadened spectrum width for different 4-ASK levels were different, therefore, by tuning the wavelength position of the 0.2 nm-bandwidth OBPF-2, the desired eye opening was significantly enlarged while other eyes were compressed so that 4-ASK detection could be achieved even using the conventional OOK receiver.

3. Results and Discussions

Experiment was demonstrated at 10 Gbaud/s and the resultant bit rate of 4-ASK signal was 20 Gbit/s. Fig. 2(a) shows the waveforms of coding process. When only one 10 Gbit/s data was injected into the EAM, the mark level induced by the 13dBm data signal was higher than that induced by 10dBm. When both of the two data signals were injected, an even higher XAM level appeared if the two '1' pulses collided in the EAM. Fig.2(b) is the corresponding eye diagram. It was found the level spacing could be easily adjusted by tuning the variable ratio optical coupler and the bias voltage of the EAM. In optical-to-noise-ratio limited systems, the optimal level spacing is around 0: 1: 4: 9 [1]. However, the practical optimal levels deviate from those values because the signal is generally band limited by the optical and the electrical filter at the receiver. The low eye is very sensitive to such filter-induced inter-symbol interference, which leads to significant power penalty. In our experiment, the level spacing was set to be around 0:1:2:4.

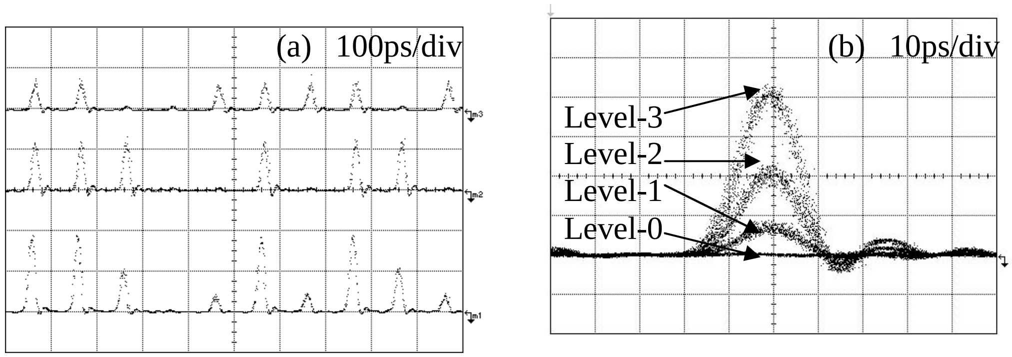

Fig. 2. The waveform (lower trace of (a)) and eye diagram (b) of 4-ask signal. XAM output signals when only 10dBm (upper trace) and 13dBm (middle trace) data was injected are also shown in (a).

Fig.3 shows the eye diagrams of the three separated 2-level eye patterns after the OBPF-2. The residual eye penalty was due to the lack of optimal operation condition for the decoding in our lab. The optimal operation with respect to the input power of EDFA-4, the property of HNLF, the wavelength position and the bandwidth of OBPF-2 depends on the pulse width and the level spacing of the input 4-ASK signal. At the anomalous dispersion operation region of the HNLF, though higher input power would broaden the spectrum even more, the noise is amplified as well due to modulation instability effect [3]. Therefore, the power of EDFA-4 in the experiment was limited to be around 9dBm, resulting in the residual eye penalty. The employment of the narrow-band OBPF-2 would help to differentiate different eyes (upper, middle, and low), but it is also sensitive to the noise and the amplitude jitter. Therefore, we believed after further optimization of the operation parameters, more reduction of the residual eye penalty can be obtained.

Fig. 4 shows the BER curves for the three separated 2-level data patterns using the all-optical decoding scheme after the transmission. The back-to-back performance for the three 2-level data patterns without the decoding scheme is also depicted in the figure. It is shown that the conventional OOK receiver cannot properly detect the 4-ASK signal. In conventional OOK detection, an electrical limiting amplifier is generally used after the photo-detector to enlarge the OOK eye opening and facilitate the threshold determination in BER detection [4]. When a 4-ASK signal is launched into such detector, the lower eye between level-0 and level-1 can be properly detected though large power penalty is induced due to the additional power consumption of other two levels. However, the middle eye between level-1 and level-2 and the upper eye between level-2 and level-3, are compressed and cannot be detected, because level-1, level-2, and level-3 operate at the saturation region of the electrical amplifier. Therefore, there were error floor for the middle and the upper eyes. By using the all-optical decoding method, however, error free operation can be achieved with a sensitivity better than -14 dBm for all the three eyes, as shown in Fig. 4. From the figure, it is also shown that the sensitivity is the best for the upper eye, while it is worst for the lower eye. Such result, however, does not imply that the upper eye has the highest OSNR. The main reason for such phenomena is that after the decoding, the probability for level 1 of the converted OOK signal is only 1/4 for the upper eye, but is 3/4 for the lowest eye. As far as the OSNR is concerned, from the slope of the curve, we can assert that the OSNR for the low eye is the highest.

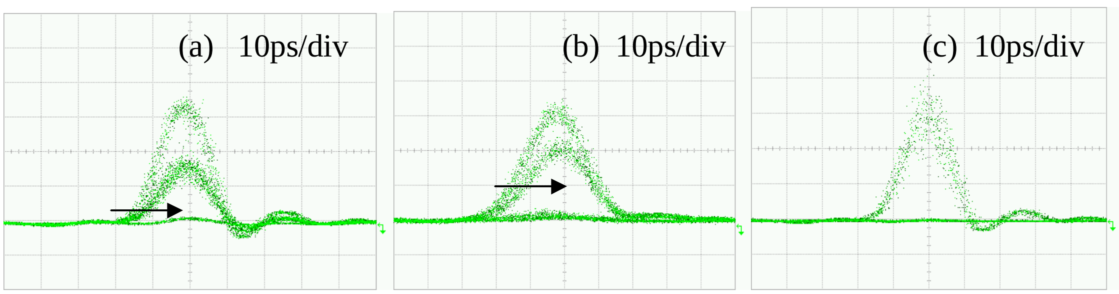

Fig. 3. Eye diagrams of the three separated 2-level eye patterns after the OBPF-2. (a), (b), and (c) correspond to the converted 2-level signals from the lower eye, the middle eye, and the upper eye of the 4-ASK signal, respectively. Arrows in (a) and (b) indicate the target eyes.

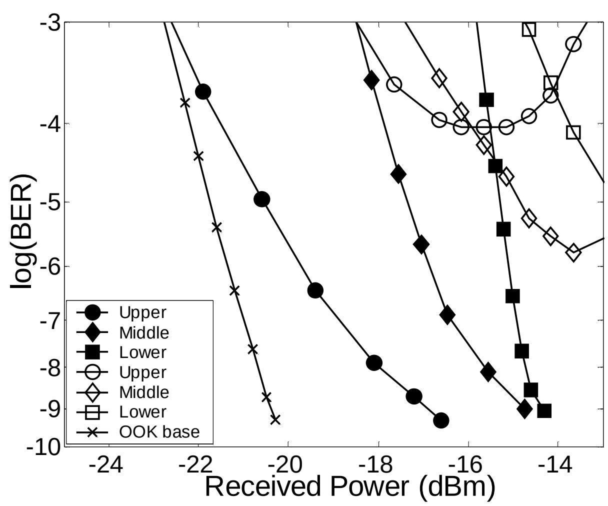

Fig. 4. BER curves for the upper eye (circle), the middle eye (diamond), and the lower eye (square) of the 4-ASK signal without (open) and with (solid) the all-optical decoding processing.

4. Conclusions

We experimentally demonstrated, for the first time, a novel all-optical 4-ASK coding and decoding technique. The coding part converted two optical OOK signals into a 4-ASK signal using EAM while the decoding part employs the HNLF with the subsequent tunable narrowband filtering to extract the different eyes from the 4-ASK signal. Performance was verified by 40km error-free transmission. Such technique features its easy implementation and the flexibility of level spacing optimization. The scheme provides a new way to upgrade the speed of legacy systems. Also it has the potential applications in format conversion, contention avoidance in future all-optical networks.

References

1. Sheldon Walklin, et al., "Multilevel signaling for increasing the reach of 10 Gb/s lightwave systems", *IEEE J. Lightwave Technol.*, Vol. 17, pp. 2235-2248(1999)
2. K. Sekine, et al., "40 Gbit/s 16-ary (4 bit/symbol) optical modulation/demodulation schemes", *Electron. Lett.*, Vol. 41, pp. 430-432 (2005)
3. T. R. Tamura, et al., "Fundamentals of stable continuum generation at high repetition rates", *IEEE J. Quantum Electron.*, Vol.36, pp.773-779 (2000)
4. G. P. Agrawal, *Fiber-Optic Communication Systems*, 3th edition, 2002, A John Wiley & Sons, Inc., New York.