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Flexible Probabilistic Shaping PON Based on Ladder-Type Probability Model

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ABSTRACT We firstly propose a novel flexible multi-rate passive optical network (PON) employing ladder-type probabilistic shaping (PS) to enable adjustable and flexible multi-rate access without changing the modulation formats. We experimentally demonstrate a ladder-type PS PON with 64-ary carrierless amplitude and phase (CAP-64) modulation in an intensity-modulation and direct-detection (IM/DD) system over 25 km standard single-mode fiber (SSMF). The results verify that the proposed method can implement a rate flexible access even when the splitting ratio of power splitter changes dynamically.

INDEX TERMS Ladder-type, probabilistic shaping, PON, flexible multi-rate access, CAP.

I. INTRODUCTION

With the further development of the Internet, higher and higher requirements of network bandwidth are needed while the data traffic is growing exponentially. Access networks are still the bottleneck that limits the performance of the entire network. How to improve the system capacity and transmission distance and enable adjustable and flexible multi-rate access of optical access network has become a key problem that must be solved under the current situation. To solve this problem, passive optical network (PON) emerges as an important technology due to its various advantages such as large capacity, simple structure, flexible scalability and transparency of support services, and it has been used extensively in broadband access networks [1]–[4]. Advanced modulation formats including carrierless amplitude and phase (CAP) modulation, discrete multi-tones (DMT) modulation, and pulse amplitude modulation (PAM) are proposed to be employed in PON. Next-generation PONs require lower complexity and better flexibility. Apparently, CAP modulation is a promising advanced modulation format based on intensity-modulation and direct-detection (IM/DD) to meet these requirements in PON [5]–[12]. Different from quadrature amplitude modulation (QAM), CAP is a single-carrier modulation format which adopts finite impulse response (FIR) filters to generate quadrature signals. Therefore, CAP is easier to implement in optical access system. The advantages of CAP include higher spectral efficiency, lower cost, higher data rate, and simpler implementation [12], [13]. Access networks require not only flexible access with low complexity, but also performance improvement such as better tolerance for nonlinearities, shaping gain, and so on.

Probabilistic shaping (PS) has been verified a promising technology for the following reasons: higher data rate, longer transmission distance, increased spectral efficiency (SE), improved sensitivity and reduced nonlinear effects [14]–[23]. In 2018, Junho Cho et al. demonstrated a trans-Atlantic field trial employing PS 64QAM and attained 18% and 80% net SE increment by employing PS, at 5523 km and 11046 km, respectively, compared with conventional QAM transmission [24]. In the same year, Jianjun Yu et al. demonstrated 8 × 506 Gb/s wavelength division multiplexing (WDM) coherent transmission for 6000 km employing PS 16QAM and high-bandwidth coherent driver modulator.

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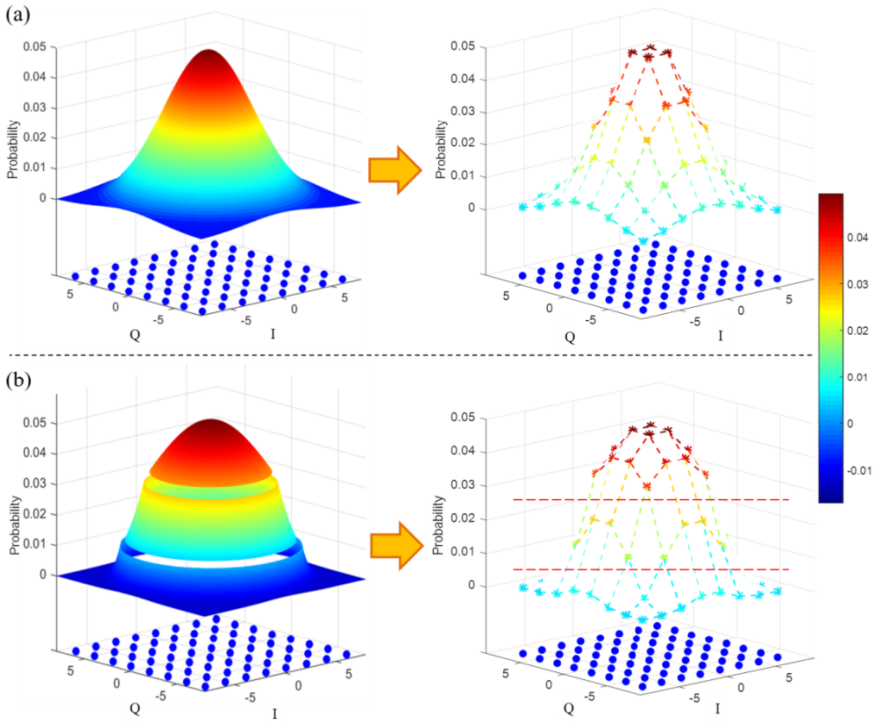

FIGURE 1. Model of conventional PS and ladder-type PS: (a) conventional PS and (b) ladder-type PS.

Furthermore, they achieved 150% transmission distance increment and 0.216 bits/symbol achievable information rate improvement with PS [25]. Furthermore, they demonstrated a PS 256QAM orthogonal frequency division multiplexing (OFDM) transmission in an IM/DD system. PS 256QAM obtained stronger nonlinearity robustness and higher achievable information rate compared with uniform 128QAM [26]. Moreover, a novel PS approach based on symbol-level labeling and rhombus-shaped constellation design was put forward in the PON system, which improved the received optical power by 2 dB compared with the conventional signaling approach [27]. The application of PS in optical access network can make the achievable capacity more approach to the Shannon limit, which gains an advantage over conventional modulation formats [15]–[17], [27], [28]. In addition, PS provides unparalleled flexibility without increasing the complexity of systems [22]. It is acknowledged that the transmission power is actually constrained because of nonlinearities. The basic idea of PS is that signal points are sent with nonuniform distribution. In other words, signal points near the origin which carry lower energy are transmitted with higher probabilities than those higher-energy signal points far from the origin. In this way, the average transmitted energy is reduced [18]. Power budget is decreased so as to afford longer transmission distance. Therefore, PS can provide a significant performance boost in optical communications. Conventional PONs usually provide different quality of service (QoS) by means of changing the modulation formats. PS is a breakthrough technology to accomplish the same or even better performance without changing the modulation formats. The access networks tend to change rapidly, and conventional PS scheme is not able to adapt to the rapidly changing transmission promptly. In order to flexibly match different rates and realize a flexible PON, it is necessary to design an innovational approach to enable adjustable and flexible multi-rate access.

In this paper, we propose and experimentally demonstrate a PS PON based on ladder-type probability model which can achieve flexible data rate as well as average signal power reduction. The total probabilities assigned to different levels are adjusted for the coarse tuning of probability grading to adapt to dynamic changes of the splitting loss in the distribution network. In addition, the fine tuning of data rates is accomplished by regulating the probabilistic distribution parameter of each level. In this way, through the step change of the ladder-type probability model, we can not only implement a multi-level rates access, but also achieve a dynamic rate change through the fine-grained adjustment of parameter of each level. We successfully carry out the experiment of ladder-type PS CAP-64 data transmission over 25 km standard single-mode fiber (SSMF). Experiment achieves multi-rate adaptation by adopting ladder-type PS. The experimental results indicate that the proposed ladder-type PS PON system is a promising candidate for the extensive applications of future access network.

II. PRINCIPLE OF LADDER-TYPE PS MODEL

Figure 1 illustrates the principle of the conventional PS and the proposed ladder-type PS. Here, we take CAP-64 for example. The image on the left of Fig. 1(a) shows the

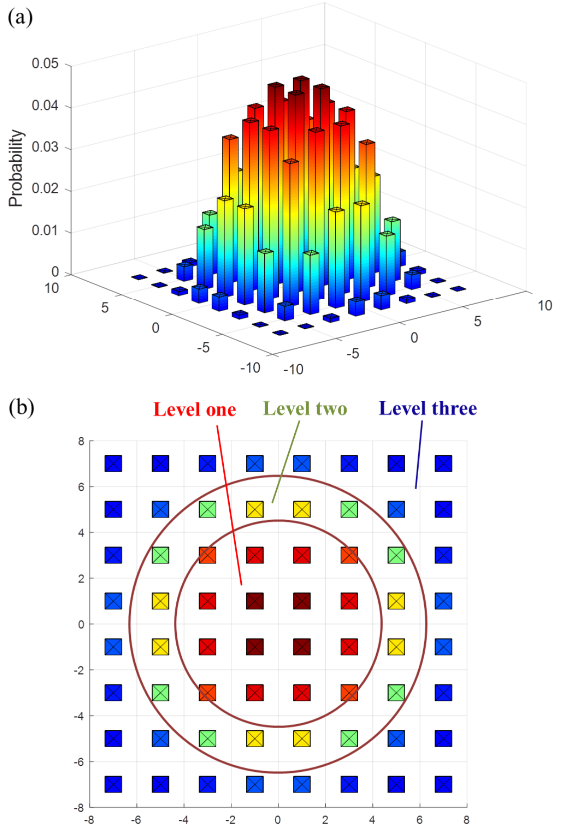

FIGURE 2. 3D and 2D graphical illustration of probabilities of ladder-type PS CAP-64: (a) 3D and (b) 2D.

probability model of conventional PS. After projecting to CAP-64 constellation, corresponding 64 discrete probabilities are obtained as illustrated on the right of Fig. 1(a). In the conventional PS scheme, the constellation symbols are distributed with nonuniform probabilities, called Maxwell-Boltzmann distribution. The transmitted symbols are independent and identically distributed (IID) discrete random variables. The probability distribution of discrete random variables is defined by the probability mass function (PMF). For CAP-M, we employ the constellation alphabet with complex constellation points $X = \{x_1, x_2, \ldots, x_M\}$, and the PMF of the transmitted symbols $x_i \in X$ is given by $P_X(x_i) = e^{-v|x_i|^2} / \sum_{x' \in X} e^{-v|x'|^2}$. Here, v is a scalar to regulate the distribution. And probability normalization is included to ensure that the probabilities add up to one. The information entropy of the input random variables is given by $H(X) = \sum_{x_i \in X} -P_X(x_i) \cdot \log_2 P_X(x_i)$ [29], [30]. We have taken the logarithm to the base 2 so that the units are in binary digits or bits. The bit rate of signals can be calculated from the baud rate and information entropy. It is given by $R_{bit} = R_{baud} \times H(X)$. Here, R_{bit} and R_{baud} are the bit rate and baud rate of signals, respectively. Nevertheless, conventional PS cannot quickly accommodate to the rapidly changing access network. Therefore, we innovatively put forward a novel ladder-type PS model as illustrated in Fig. 1(b). Here, we divide CAP-64 into three levels. The principle also applies to high order CAP. For CAP-M, we employ a lookup table to determine alternative boundaries leading to ladder-type levels. N_S refers to the serial number of constellation circles from the inside out. The lookup table for CAP-4096 is shown in TABLE 1. We adopt the third and fifth circles as the boundaries in the CAP-64 scheme as shown in Fig. 2 (b). Fig. 2 (a) is the three dimensional (3D) diagram illustrating the probabilities of ladder-type PS CAP-64 in the space model.

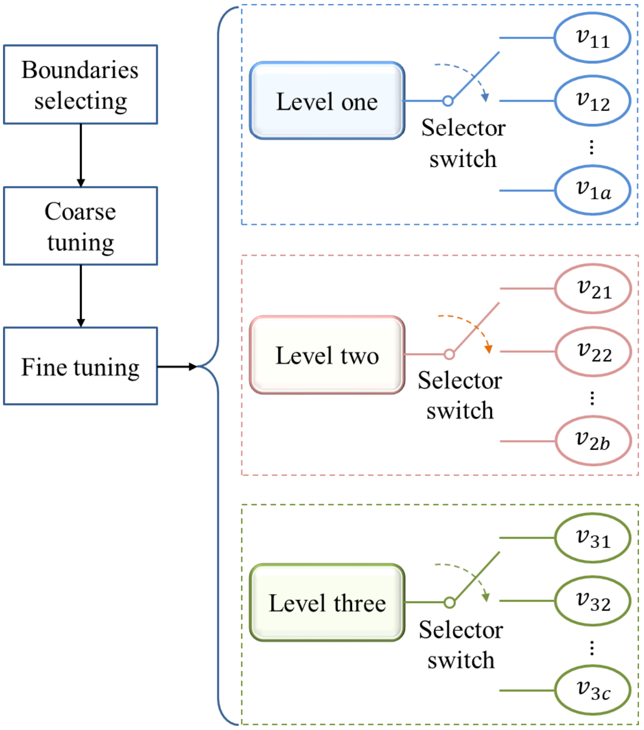

FIGURE 3. The flow of probabilities selection of ladder-type PS CAP-64.

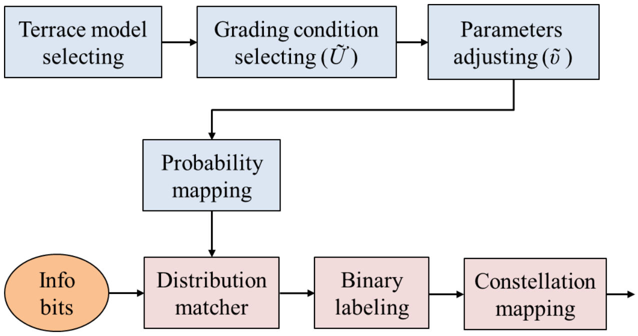

FIGURE 4. Diagram of ladder-type PS distribution module.

The specific rate adaption progress is illustrated in Fig. 3. Level boundaries are selected according to the lookup table and rate requirement. And then different total probabilities $\tilde{U} = \{U_1, U_2, \ldots, U_m\}$ are assigned to different levels with a corresponding $\tilde{v}$, for coarse adjustment, which can provide a dynamic response to the dynamic step change of the splitting loss in the distribution network. Here, m refers to the total number of ladder-type levels. And the sum of $\tilde{U}$ is one. In order to accomplish fine tuning of rate, m selector switches are employed. The value of m is three for CAP-64

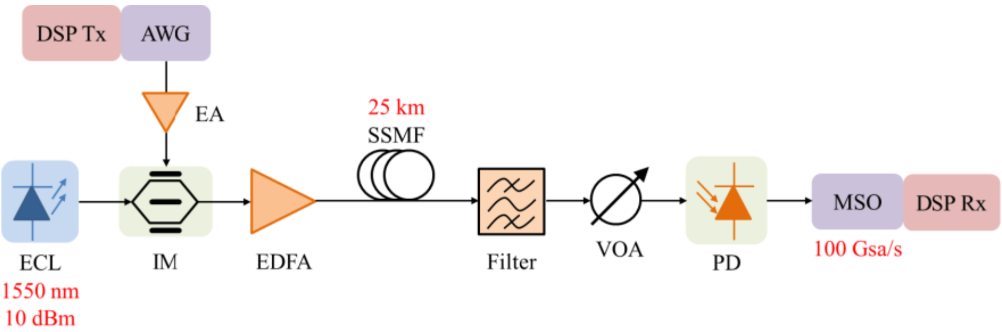

FIGURE 5. Experimental setup (ECL: external cavity laser; AWG: arbitrary waveform generator; EA: electrical amplifier; IM: intensity modulator; EDFA: Erbium-doped fiber amplifier; SSMF: standard single-mode fiber; VOA: variable optical attenuator; PD: photodiode; MSO: mixed signal oscilloscope).

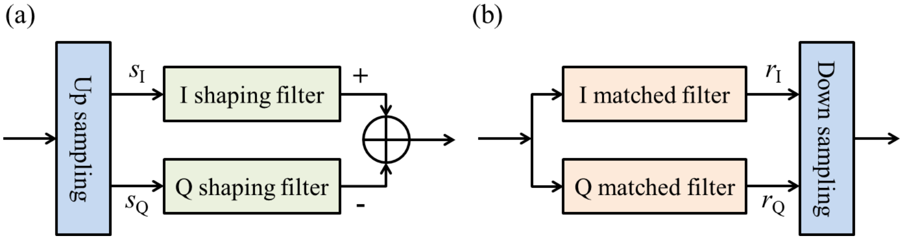

FIGURE 6. Schematic diagram of CAP modulation and demodulation: (a) modulation and (b) demodulation.

TABLE 1. Lookup Table for CAP-4096.

Boundaries (N_S)	Corresponding quasi order
3	16
5	32
8	64
15	128
30	256
54	512
103	1024
196	2048
398	4096

demonstrated in this paper. In the fine granularity adjustment of rate, the three levels employ a, b and c options, respectively. By choosing $v_1 \in \{v_{11}, v_{12}, \ldots, v_{1a}\}$, $v_2 \in \{v_{21}, v_{22}, \ldots, v_{2b}\}$, and $v_3 \in \{v_{31}, v_{32}, \ldots, v_{3c}\}$ in each level respectively, fine rate tuning is accomplished. $\tilde{v} = \{v_1, v_2, v_3\}$. Diagram of ladder-type PS distribution module is shown in Fig. 4. After parameters adjustment that is illustrated in Fig. 3, the resulting probability distribution P_X of the constellation points is mapped to the distribution matcher (DM). The distribution matcher transforms information bits into nonuniform symbols according to P_X [31]. Then we adopt binary labels to represent the nonuniformly distributed symbols. The output binary bits are then mapped to constellation symbols, and the modulated constellation is distributed as shown in Fig. 2. At the end of distribution module shown in Fig. 4, the output data is modulated with CAP. After the offline digital signal processing (DSP), ladder-type PS CAP-64 signals are obtained.

III. EXPERIMENT AND RESULTS

Figure 5 shows the experimental setup of the proposed ladder-type PS CAP-64 system over 25 km SSMF, where IM/DD is adopted for demonstration. At the transmitter, offline DSP is employed to generate the ladder-type PS CAP-64 signals according to Fig. 4 and Fig. 6 (a). Fig. 6 (a) shows the detailed CAP modulation architecture. To be specific, firstly pseudo random binary sequence (PRBS) with length of $2^{15}-1$ undergoes the process of ladder-type PS distribution as shown in Fig. 4 to generate corresponding symbol signals. Afterwards, the signals are up-sampled with a sampling factor of 5. Then the real and imaginary parts of the signals are separated and sent to corresponding shaping filters. The roll-off factor of the filters is set to 0.2. After shaping filtering, the two outputs are combined in the form of subtraction and sent into an arbitrary waveform generator (AWG, Tektronix AWG70002A) with sample rate of 25 GSa/s and resolution of 8 bits. After amplified by an electrical amplifier (EA), the generated electrical signal is used to drive the Mach-Zehnder modulator (MZM). A continuous-wave (CW) lightwave at 1550 nm with 10 dBm output power is generated by an external cavity laser (ECL) and fed into the MZM to accomplish the intensity modulation. The generated optical signal from intensity modulator (IM) is boosted by an erbium-doped fiber amplifier (EDFA) and then launched into 25 km SSMF. The launch power into the fiber is 5 dBm. After passing through a 25 GHz optical filter, a variable optical attenuator (VOA) is employed to change the received optical power. The received optical signal is detected by a 40 GHz photodiode (PD). The analog to digital conversion is

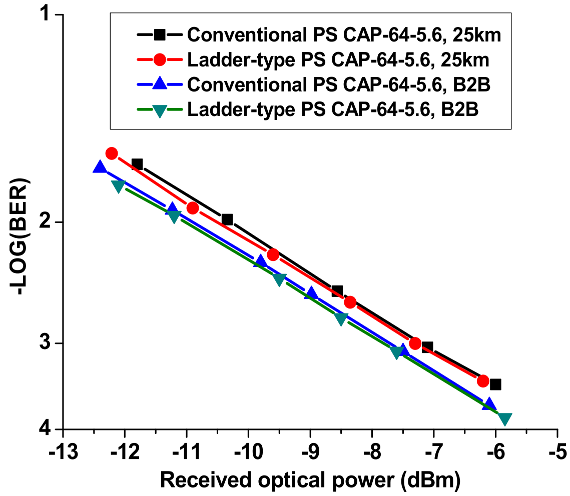

FIGURE 7. BER versus received optical power for conventional PS CAP-64 and ladder-type PS CAP-64 (B2B: back-to-back).

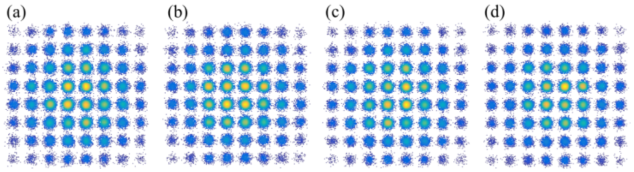

FIGURE 8. Constellations of the conventional PS CAP-64 and ladder-type PS CAP-64 signal: (a) conventional PS CAP-64 after 25 km, (b) ladder-type PS CAP-64 after 25 km, (c) conventional PS CAP-64, B2B, and (d) ladder-type PS CAP-64, B2B.

performed by a mixed signal oscilloscope (MSO, Tektronix MSO 73304DX) with 100 GSa/s sample rate. Finally, the signal is processed through offline DSP. The receiver DSP splits the signal into real and imaginary parts followed by corresponding matched filters and down-sampling as shown in Fig. 6 (b). After demapping, inverse binary labeling and inverse distribution matching, the signal is recovered to information bits for further analysis. In the experiment, the baud rate of signals is set to 5 Gbaud, and the corresponding bit rate can be calculated from the baud rate and information entropy.

Figure 7 shows the measured bit error ratio (BER) for conventional PS CAP-64 and ladder-type PS CAP-64 after 25 km fiber transmission and back-to-back transmission. The curves of BER versus received optical power are measured in four different cases. As depicted in the legend of Fig. 7, "PS CAP-64-$H(X)$" denotes the separate PS CAP-64 whose information entropy is $H(X)$. The same goes for the legends of Fig. 9 and Fig. 11. The bit rate in Fig. 7 is 28 Gb/s. Here, the parameter v is set to 0.0336 in conventional PS scheme, and the corresponding information entropy is $H(X)$ =5.6. And for the proposed scheme, $\tilde{U} = \{0.55, 0.23, 0.22\}$, $\tilde{v} = \{0.04, 0.04, 0.04\}$. As shown in Fig. 7, the proposed ladder-type PS scheme has almost the same BER performance as conventional PS scheme, without decreasing receiver sensitivity. The power penalty is about 0.5 dB after 25 km fiber transmission. The constellation diagrams of the four different cases are illustrated in Fig. 8.

According to the proposed ladder-type probability model, for CAP-64 modulation, we first implement a multi-level rates access with large rate granularity by assigning different total probabilities $\tilde{U} = \{U_1, U_2, U_3\}$ to the three levels and adopting a corresponding $\tilde{v}$ for coarse adjustment of rate. The measured BER curves for conventional PS CAP-64 and ladder-type PS CAP-64 with 1 bits/symbol rate granularity are illustrated in Fig. 9. The corresponding data rates in Fig. 9 are 28 Gb/s, 23 Gb/s, 18 Gb/s and 13 Gb/s respectively, and the rate interval is 5 Gb/s. We can get the conclusion that the BER performance of the proposed ladder-type PS scheme and conventional PS scheme are basically identical. In the coarse adjustment of rate, the smaller the information entropy, the better BER performance can be obtained. The constellations of ladder-type PS CAP-64 signal are shown in Fig. 10. Changes of modulation formats in conventional PONs can be seen as the limiting cases of the ladder-type PS CAP-64. That is, we adopt the assignment of $\tilde{U}$ instead of changing the modulation format. $\tilde{U} = \{0.25, 0.25, 0.5\}$, $\{0.5, 0.5, 0.0\}$, and $\{1.0, 0.0, 0.0\}$ with $\tilde{v} = \{0.0, 0.0, 0.0\}$ are in correspondence to CAP-64, CAP-32 and CAP-16, respectively. When the splitting ratio of power splitter dynamically changes, the proposed ladder-type PS scheme can provide a dynamic response to the step change, which offers significant superiority to the conventional PS scheme.

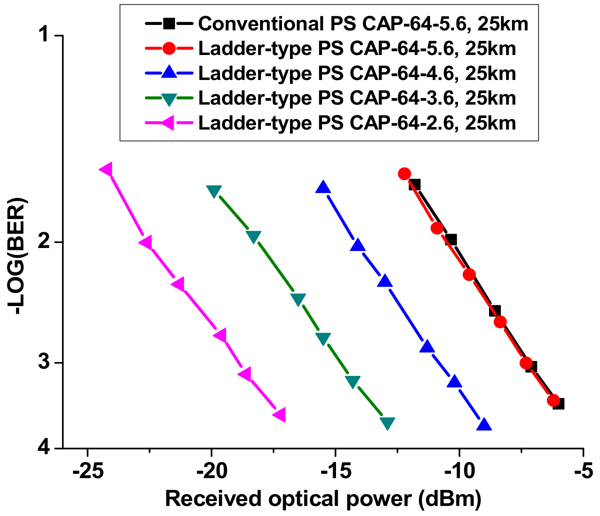

FIGURE 9. BER versus received optical power for conventional PS CAP-64 and ladder-type PS CAP-64 with 1 bits/symbol rate granularity.

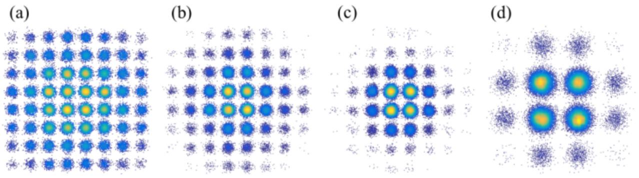

FIGURE 10. Constellations of the ladder-type PS CAP-64 signal: (a) 5.6 bits/symbol, (b) 4.6 bits/symbol, (c) 3.6 bits/symbol, and (d) 2.6 bits/symbol.

Based on the large granularity rate change of the ladder-type PS CAP-64, the value of $\tilde{v}$ is adjusted to accomplish the fine tuning of data rates. Here, we take the fine tuning of data rates based on ladder-type PS CAP-64-3.6 and ladder-type PS CAP-64-5.6 as an example. By regulating the value

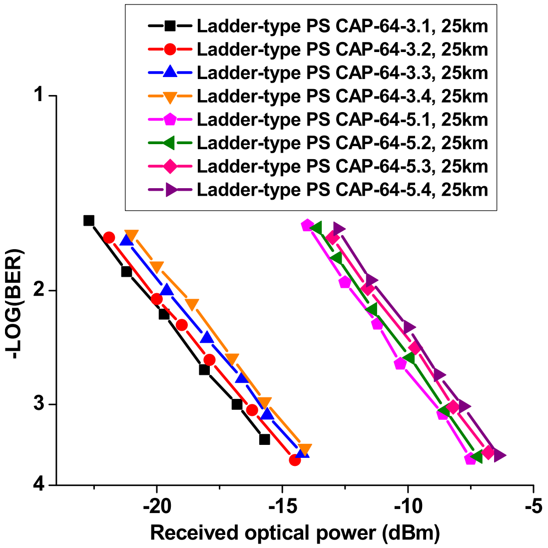

FIGURE 11. **BER versus received optical power for ladder-type PS CAP-64 with 0.1 bits/symbol rate granularity.**

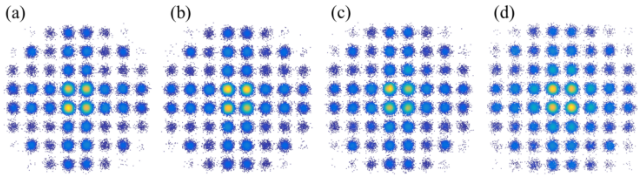

FIGURE 12. **Constellations of the ladder-type PS CAP-64 signal: (a) 5.1 bits/symbol, (b) 5.2 bits/symbol, (c) 5.3 bits/symbol, and (d) 5.4 bits/symbol.**

of $\tilde{v}$, a rate granularity of 0.1 bits/ symbol is realized. Symbols in each level are distributed with Maxwell-Boltzmann distribution. The measured BER curves for ladder-type PS CAP-64-3.1∼3.4 and ladder-type PS CAP-64-5.1∼5.4 with 0.1 bits/ symbol rate granularity are illustrated in Fig. 11. The corresponding data rates in Fig. 11 are 15.5 Gb/s, 16 Gb/s, 16.5 Gb/s, 17 Gb/s, 25.5 Gb/s, 26 Gb/s, 26.5 Gb/s, and 27 Gb/s respectively, and the rate interval is 0.5 Gb/s in each group. In the fine adjustment of rate, the smaller the information entropy, the better BER performance can be obtained. The constellations of the ladder-type PS CAP-64-5.1∼5.4 signal are illustrated in Fig. 12. By combining coarse adjustment with fine adjustment, we can not only implement a coarse-grained multi-level rates access, but also achieve a fine-grained dynamic rate change through the adjustment of $\tilde{v}$ based on coarse adjustment.

IV. CONCLUSION

We have proposed a novel flexible multi-rate PON employing ladder-type PS to enable adjustable and flexible multi-rate access without changing the modulation formats. A ladder-type PS PON with CAP-64 modulation in an IM/DD system is successfully demonstrated over 25 km fiber link. The proposed scheme maintains almost identical BER performance as conventional PS scheme at the same bit rate, without reducing receiver sensitivity. There is about 0.5 dB power penalty after 25 km fiber transmission. In both coarse adjustment and fine adjustment of rate, smaller information entropy leads to better BER performance. By combining rate coarse tuning with fine tuning which is accomplished by adjusting $\tilde{U}$ and $\tilde{v}$, respectively, the proposed scheme has implemented a rate flexible access. Both 5 Gb/s and 0.5 Gb/s rate intervals are accomplished in the experiment. When the splitting ratio of power splitter dynamically changes, the proposed ladder-type PS scheme can provide a dynamic response to the dynamic step change of the splitting loss in the distribution network, which offers significant superiority to the conventional PS scheme. Moreover, the average signal power is reduced which leads to energy-efficiency. The experimental results verify the superiority of the proposed ladder-type PS PON in next generation PONs.

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