Performance Enhancement in RSOA-Based WDM Passive Optical Networks Using Level Coding

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***Abstract*—Reflective semiconductor optical amplifier has been widely employed in wavelength-division-multiplexed passive optical network (WDM-PON) for implementing colorless optical network unit. WDM-PONs using a single-feeder fiber is economically beneficial, but vulnerable to beat noise resulted from distributed and discrete reflections. In this paper, we present a novel technique exploiting simple digital signal processing to mitigate the impairments in single-feeder WDM-PON by means of introducing correlations between signal levels in a coding process. The correlation properties of the coded sequence permits overall spectrum shaping to suppress the low-frequency components. We apply dicode code, the simplest correlative level code that enables direct current balance, in the uplink of a WDM-PON with downstream continuous-wave seed light or in the downlink of a WDM-PON with remodulated upstream signal. In the first case, the system's reflection tolerance is substantially enhanced via the dicode-coded modulation in the uplink. Moreover, the system reach is extended by 15 and 25 km for data rate of 2.5 and 1.25 Gb/s, respectively. In the second case, a 60 km full-duplex WDM-PON with 10 Gb/s dicode-coded downlink and 2.5 Gb/s remodulated uplink is demonstrated with high robustness against the remodulation and reflection noise.**

***Index Terms*—Rayleigh backscattering (RB), reflection, semiconductor optical amplifier (SOA), wavelength-division multiplexing (WDM).**

I. INTRODUCTION

THE rapidly growing bandwidth demand drives the access network toward ultrahigh capacity which is beyond what a time-sharing solution can support. Wavelength-division-multiplexed passive optical network (WDM-PON) has been recognized as a promising solution to the next-generation fiber-to-the-home system. The assignment of dedicated wavelength to each subscriber enables WDM-PON to provide fast connection, secure communication, and graceful upgradability [1]–[4]. Despite of these advantages, the commercialization of WDM-PON still remains a challenge owing to high installation expenditure. The colorless operation of optical network unit (ONU) is desired in WDM-PON for mass production, cost reduction, and centralized wavelength management. The Reflective semiconductor optical amplifier (RSOA) capable of simultaneous amplification and modulation offers an attractive option for the colorless upstream transmitter. The gain provided by the RSOA relieves the problem of double link loss in the uplink of WDM-PON based on loop-back architecture.

The RSOA requires a seed light delivered from the optical line terminal (OLT). Extensive studies have been carried out on WDM-PONs using continuous-wave (cw) light to seed RSOAs [5]–[9]. In this scheme, the OLT sends downstream (DS) signals and cw light in different wavelength bands to ONUs. The upstream (US) signal is modulated on the cw light and reflected back to the OLT. Since the seed light and the US signal are transmitted at the same wavelength in one fiber, the reflected cw light due to Rayleigh backscattering (RB) or discrete reflections (DR) will interfere with the signal and seriously degrade the US performance [10]–[12]. RB, as an intrinsic property of optical fiber, results in distributed small reflections along light propagation. DR, on the other hand, is originated from fiber-end facets and network elements with low return loss. Many techniques have been reported to overcome RB and DR in single-fiber WDM-PON, including frequency dithering [13], phase modulation [14], [15], radio-frequency (RF) tone [16], and electrical equalization [17].

An alternative configuration for RSOA-based WDM-PON is to remodulate the DS signal for US transmission. Networks based on cw-light-seeded RSOAs require twice the optical bandwidth of those based on DS-signal-seeded RSOAs, when the channel spacing is fixed. Previous reports on wavelength-reused WDM-PON have explained its merits and weaknesses [18]–[20]. This type of network halves the number of lasers and doubles the maximal supported subscribers within the *C*-band. However, the amplitude-remodulated uplink is prone to intensity noise caused by the residual DS signal. There have been numerous attempts to resolve this issue, by utilizing, for example, gain-saturated ONUs [21], orthogonal modulation formats in up- and downlinks [22], [23], and subcarrier multiplexing [24], [25]. In addition, the wavelength-reused WDM-PONs are also vulnerable to backreflections as the up- and downlinks are operated on the same carrier.

In this paper, we present a novel cost-effective solution that involves spectral shaping to increase the maximal allowable DS extinction ratio (ER_d) in WDM-PON using remodulation scheme, and enhance the reflection tolerance in both two types of WDM-PONs. The proposed technique correlates the signal levels via encoding the original data stream to reform the signal spectrum with much fewer low-frequency components. This correlative level (CL) coding scheme reduces crosstalk penalties via altering the signal spectrum to separate it from the interferers. Previously spectral-shaping methods have been proven effective in RB reduction [26]–[29]. In contrast, the utilized CL coding has the advantages of simplicity and zero overhead. In

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the case where cw light is used to seed the RSOA, the experiments verify that the reflection tolerance of dicode-coded uplink is substantially enhanced compared with the uncoded uplink. Moreover, the system reach is extended to 60 and 90 km at rate of 2.5 and 1.25 Gb/s, respectively. In the case where DS signal is used to seed the RSOA, we demonstrate a 40 km reach extension for the WDM-PON with 10 Gb/s dicode-coded downlink and 2.5 Gb/s ON–OFF keying uplink. Furthermore, the proposed system allows higher ER_d, lower US extinction ratio (ER_u), and more reflection noise.

The rest of this paper is organized as follows. In Section II, we explain the principles of level-coding technique and describe the configurations of the two types of WDM-PONs. The experimental investigations on the performance of dicode coding in single-fiber WDM-PONs, together with the discussions of the obtained results, are presented in Section III. Finally, this paper is summarized in Section IV.

II. OPERATING PRINCIPLES

A. Dicode Level Coding

The investigations on CL coding reveal that the generation of a signal with correlated levels permits overall spectrum shaping in addition to the individual pulse shaping [30], [31]. CL codes introduce controlled intersymbol interference between adjacent symbols, resulting in 1 bit/symbol multilevel signals. Duobinary, one of the CL codes, has been exploited in WDM-PON to operate the RSOA at high speed [32]. Unlike duobinary code that can compress the signal energy into low frequencies, some other CL codes are able to redistribute the signal energy so as to eliminate the dc and move the energy to higher frequencies. Different with the reported duobinary modulation to increase the uplink capacity [32], in this paper, a dc-balanced CL code is utilized to upshift the signal content in the low-frequency region to higher frequencies, for the purpose of reducing the spectral overlap between the signal and the interferers. CL codes that have a coding transfer function containing the polynomial of $(1-D)$, where D is a 1-bit delay, force spectral null at dc in the coded signal [33]. The selected CL code in our proposed systems is the dicode code which has the simplest form among all dc-balanced CL codes. Dicode code is characterized by its transfer function as $(1-D)$. Fig. 1(a) illustrates the dicode coding process as a delay-and-subtract register that can be simply realized by a delay line and a power combiner. In order to treat the correlated signal levels independently in the decoding process, the original binary message needs to be differentially coded prior to the CL encoding. Fig. 1(b) sketches the procedures of the differential precoding realized by a delay line and two logical gates. The output and input sequences of the coders in Fig. 1(a) and (b) give an example of the coding results. Thanks to the precoding, the dicode-coded symbols in Fig. 1(a) have a one-to-one relationship with the original binary symbols in Fig. 1(b). Then, the dicode decoding can be conducted bit-by-bit, following the rule that level “1” and “−1” corresponds to binary “0,” and level “0” corresponds to binary “1.” Hence, the decoding can be simply accomplished by means of a full-wave rectifier. The one-to-one relationship also confirms that unlike the dc-balanced line codes such as 8 b/10 b code [34] and Manchester code [35], dicode coding imposes no bandwidth redundancy or complex circuitry. This merit of dicode coding is particularly beneficial for bandwidth-limited channels.

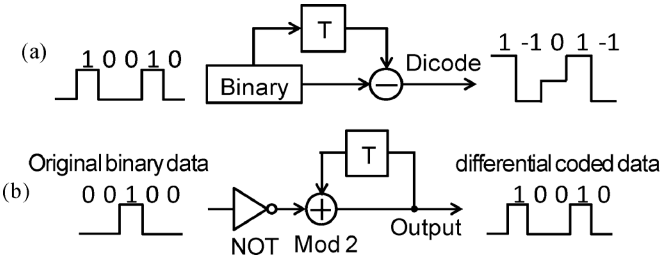

Fig. 1. (a) Dicode coding diagram. (b) Differential encoding of the data prior to dicode encoding; T is 1 bit period.

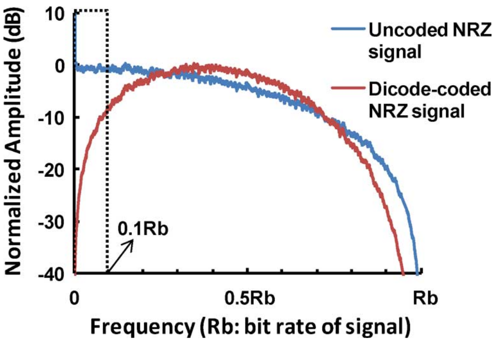

Fig. 2. RF spectra of uncoded and dicode-coded NRZ signals.

The measured spectra of the dicode-coded nonreturn-to-zero (NRZ) signal and the uncoded NRZ signal are displayed in Fig. 2. It is clear that the dicode-coded signal has much less baseband components compared with the uncoded one, especially within the bandwidth of 10% bit rate of the signal. It is seen from Fig. 2 that a great portion of the signal energy is moved from the baseband to around the middle of the signal bandwidth through level coding. The reflection noise in the WDM-PON with cw seed light has high concentration near the dc frequency. Without level coding, the reflected cw light beats with the US signal, resulting in crosstalk peaked at frequencies near dc. For wavelength-reused WDM-PON, the dicode coding can mitigate the crosstalk as well by shaping the power of the DS signal into different distribution from the US one. In addition, since dicode level coding has straightforward implementation circuit and no coding overhead, it has a great potential for single-fiber access systems.

B. Single-Feeder WDM-PON Employing RSOA Seeded by CW Light and With Dicode-Coded US Signal

The schematic diagram of the proposed single-feeder WDM-PON system using cw seed light for the uplink and dicode-coded US signal is illustrated in Fig. 3(a). In this type of network, the DS signals and cw lightwaves are provided from the OLT, but allocated in different wavelength bands. The DS signal is detected by its corresponding ONU. The cw light is fed to the RSOA for amplification and modulation. Then, the US signal is reflected and transmitted through the same fiber back to the OLT. Since the US and cw light are operated at the same wavelength band, the back-reflected cw light beats with the US signal, inducing interferometric crosstalk. The downlink signal only suffers from double RB or reflection that has negligible small power. Therefore, the transmission performance and

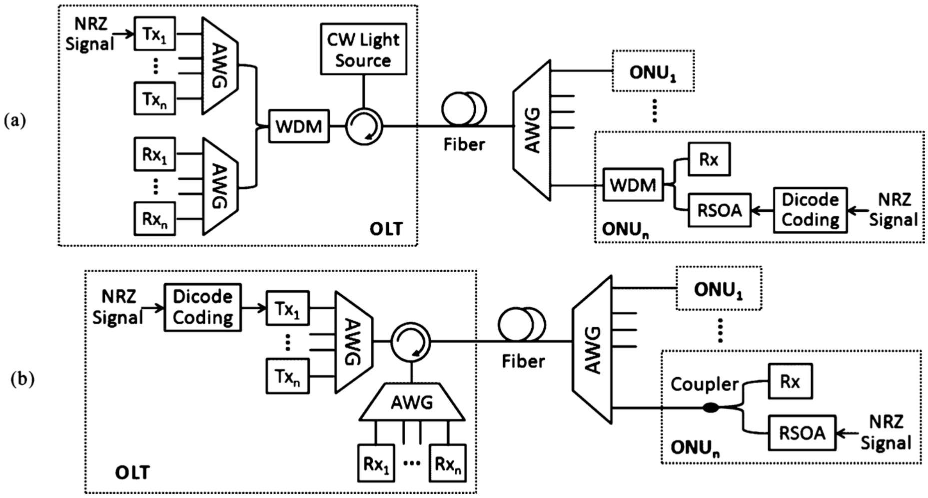

Fig. 3. Configurations of the proposed single-feeder WDM-PONs employing the RSOA: (a) seeded by cw light and modulated by dicode-coded US signal; and (b) seeded by dicode-coded DS signal.

the system reach are mostly limited by the uplink. Thus, it would be beneficial to make use of dicode level coding in the US transmission, since the reflection noise has high spectral concentration at low frequencies. The reflected cw light owing to RB occupies a narrow bandwidth that is around twice the laser linewidth. The discretely reflected cw light also has very small bandwidth which is exactly the same with the linewidth of the light source. Hence, the upshift of the signal spectrum produced by dicode level coding allows the suppression of both types of reflection noise.

C. Single-Feeder WDM-PON Employing RSOA Seeded by Dicode-Coded DS Signal

The schematic diagram of the proposed single-feeder WDM-PON system based on the dicode-coded DS signal-reuse configuration is illustrated in Fig. 3(b). In this type of network, the DS signals are externally modulated onto different carriers and wavelength multiplexed by an arrayed waveguide grating (AWG) at the OLT, before being launched into the feeder fiber. After demultiplexing, at the ONU, a portion of the received DS signal is detected by the US receiver, and the other portion is delivered to the RSOA for amplification and remodulation. The remodulated US signal is reflected back and transmitted through the same fiber to the OLT. Since the US and DS signals are operated at the same wavelength band, a circulator is used to separate these two groups of signals at the OLT. Afterward, the US signals can be demultiplexed by an AWG and sent to their respective receivers. If the same modulation format is used for both US and DS directions, the residual DS signal and the remodulated signal will fall in the same frequency band, causing intensity fluctuations on the mark level of the US signal. Operating the RSOA in gain saturation can minimize the remodulation noise, but demanding high input power to the ONU and shrinking the power margin. In this network, the dicode level coding is applied in the downlink which usually works at higher bit rate than the uplink, while the ONU sends the uncoded NRZ signal to the OLT. The adopted dicode coding can restrain the intensity noise and allows high ER_d since the spectral overlap of the DS and US signals is greatly decreased; thus, the system power budget increases since gain saturation at the user terminal is no longer compulsory.

III. EXPERIMENTAL DEMONSTRATIONS

A. Single-Feeder WDM-PON Employing RSOA Seeded By CW Light and Modulated by Dicode-Coded US Signal

The experimental setup is depicted in Fig. 4. The cw light at 1550 nm is generated by a distributed feedback laser with a linewidth of about 2 MHz. After passing through a length of standard single-mode fiber (SSMF), the light is injected into an RSOA that has a 3 dB electrical bandwidth of 1 GHz. The RSOA is directly modulated by a $2^{15} - 1$ pseudorandom binary sequence (PRBS) with or without dicode coding at the rate of 1.25 or 2.5 Gb/s. At the US receiver, the power of the US signal and RB noise is monitored by a power meter through a 90:10 coupler. The received optical signal-to-RB ratio (OSRR) is calculated as the power ratio when the RSOA is ON and OFF, and adjusted by varying the launched power of seed light. A variable attenuator is put in front of the photodetector (PD) to control the received optical power. After PD, for uncoded transmission, the signal is passed through a low-pass filter (LPF) having the same cutoff frequency with the data rate to eliminate the out-of-band noise. On the other hand, the dicode reception is composed of a high-pass filter (HPF) with the cutoff frequency of about 2% of the data rate to filter out reflection noises, and the same LPF as the one used in the NRZ receiver. After that, the signal needs to be decoded into binary signal. Due to the lack of a full-wave rectifier, the received signals are captured by a storage oscilloscope with a length of 2×10^6 bits for digital rectification and bit error rate (BER) calculation. Eye diagrams of the signals at points (a), (b), and (c) on the system setup are displayed in Fig. 4 as well.

At first, the bit rate and the fiber length are set to 1.25 Gb/s and 20 km for the RB tolerance investigation. The BER results are measured as a function of OSRR for both conventional binary modulation and dicode modulation with HPF, shown by Fig. 5. The launched seed power is varied to change the OSRR from 22.2 to 15.1 dB. The result in dash circle is estimated from the signal-to-noise ratio (SNR) due to the limited storage capacity. At BER of 10^{-4}, the dicode signal has around 3.5 dB improvement in reflection tolerance over the NRZ signal. With 7% forward error correction (FEC), the minimal OSRR to recover error-free dicode signal is about 17 dB using the dicode level

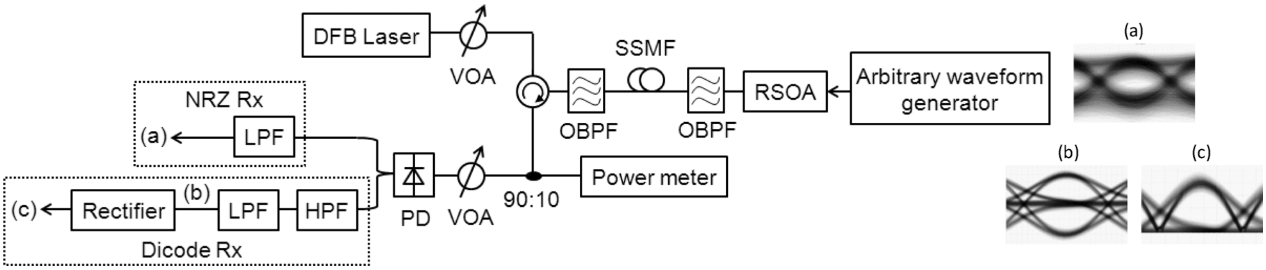

Fig. 4. Experimental setup of WDM-PON with RSOA seeded by cw light and eye diagrams at points (a), (b), and (c); VOA is variable optical amplifier.

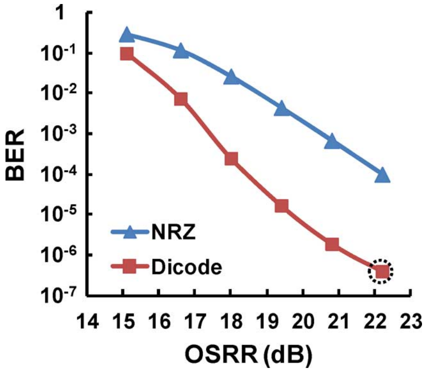

Fig. 5. BER versus OSRR in WDM-PON with cw seed light.

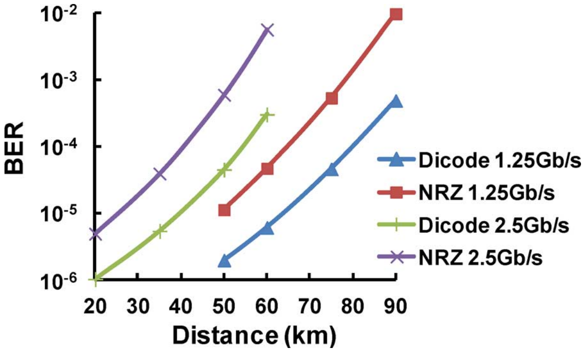

Fig. 6. BER versus transmission distance in WDM-PON with cw seed light.

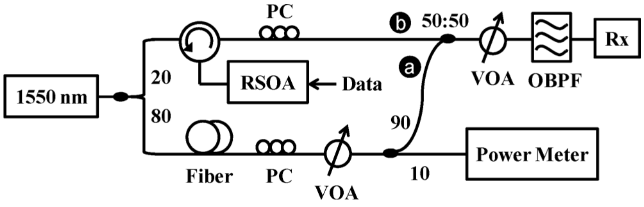

Fig. 7. Experimental setup for reflection tolerance study in WDM-PON with cw seed light; PC is polarization controller.

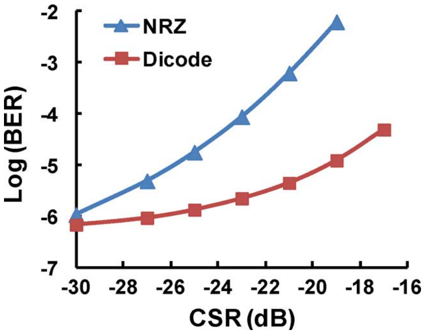

Fig. 8. BER versus CSR in WDM-PON with cw seed light.

coding. Furthermore, the power budget that can be enlarged by allowing higher input power of cw light is increased by 3 dB in this system configuration. The insets in Fig. 4 give the eye diagrams of the detected signal at OSRR of 19.4 dB. It is obvious that the received binary signal (inset (a) in Fig. 4) is seriously degraded by RB, and the superior performance of the proposed approach is verified by the clear eye of the dicode signal (inset (b) in Fig. 4) and its converted binary signal (inset (c) in Fig. 4). The increased allowable seed power by dicode coding has the potential for longer reach. In order to examine its capability of reach extension, the BERs at data rates of 1.25 and 2.5 Gb/s are measured against the transmission distance. The results compared between dicode and NRZ formats are given in Fig. 6. The US transmission can be achieved below 7% FEC limit of 2×10^{-3} over 60 and 90 km bidirectional fiber for 2.5 and 1.25 Gb/s, respectively. It is seen that the achievable uplink reach by dicode modulation is 13 to 16 km longer than the conventional method for data rate of 2.5 and 1.25 Gb/s, respectively.

To evaluate the capability of dicode coding in mitigating only the reflected cw light, we carry out experiment at 1.25 Gb/s with setup shown by Fig. 7 for the obtained BERs in Fig. 5 are also influenced by Brillouin backscattering and signal reflections. First, the seed light is split into two branches. The upper branch generates the signal, while the other produces the crosstalk of cw light. Fig. 8 shows the measured BERs against the crosstalk-to-signal ratio (CSR) which is the power ratio between point “a” and point “b” in Fig. 7. The crosstalk level is adjusted by tuning the VOA in lower branch and monitored by the power meter. It is clearly seen from Fig. 8 that the dicode coded transmission tolerates 6.5 dB more cw reflections than the uncoded NRZ one at BER of 5×10^{-5}.

B. Single-Feeder WDM-PON Employing RSOA Seeded by Dicode-Coded DS Signal

The proposed wavelength-reused system is experimentally demonstrated on one channel at 1550 nm, with the setup shown in Fig. 9. At the OLT, 10 Gb/s DS signal is generated by externally modulating a 20 GHz electroabsorption modulator (EAM) with a dicode-coded $2^{15} - 1$ PRBS. The signal is then launched into a variable length of SSMF. Two optical bandpass filters (OBPF) at the ends of the fiber simulate the AWG. Inside the user module, the received DS signal is split by a 50:50 optical coupler into two paths: one is detected by the DS receiver, and the other is fed to an RSOA with a 3 dB bandwidth of 1 GHz. The DS receiver consists of a 20 GHz PD, an HPF with 150 MHz cutoff frequency for the dicode DS signal to suppress the crosstalk caused by the reflected US signal, and a 10.5 GHz LPF

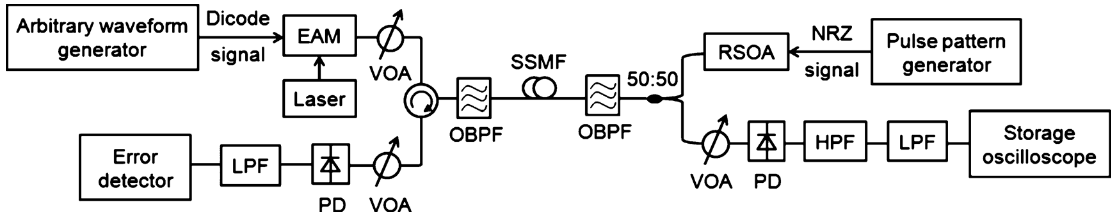

Fig. 9. Experimental setup of WDM-PON with RSOA seeded by dicode-coded DS signal.

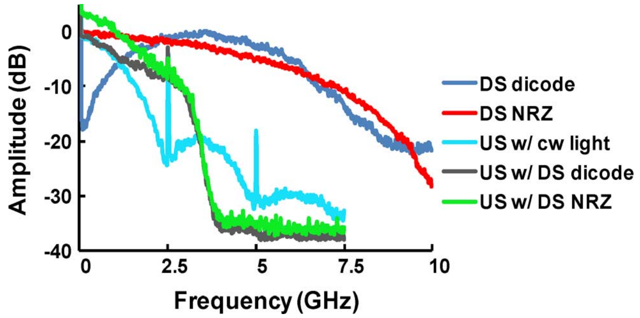

Fig. 10. Spectra of DS dicode/NRZ signals and US NRZ signals remodulated on different seed light.

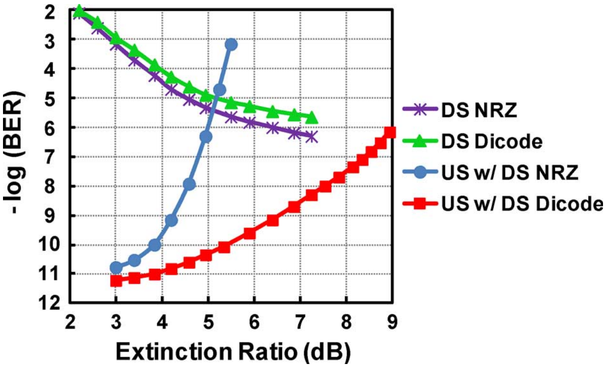

Fig. 11. BER of the downlink and the uplink against the ER_d.

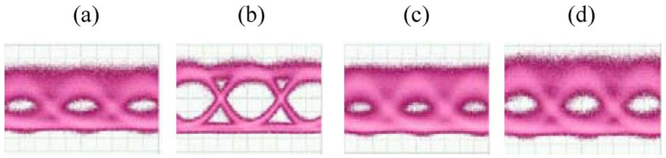

Fig. 12. Eye diagrams of b2b US signals seeded by (a) DS dicode signal w/o LPF, (b) DS dicode signal w/ LPF, (c) DS binary signal w/o LPF, and (d) DS binary signal w/ LPF.

to minimize other noises. Due to the lack of a full-wave rectifier, the received DS dicode signal is captured by a storage oscilloscope for binary conversion and BER calculation. For US transmission, the RSOA biased at 60 mA is directly modulated by a 2.5 Gb/s $2^{15}-1$ PRBS signal. At the US receiver, the signal is detected by a 3 GHz PD, and passed through a 2.7 GHz LPF to filter out the residual DS signal. The LPF is used in all cases unless specified.

The measured RF spectra of the 10 Gb/s DS signals and the 2.5 Gb/s US signals modulated on cw light, modulated on dicode signal after an LPF, and modulated on NRZ signal after an LPF are plotted in Fig. 10. Unlike the NRZ signal, the 10 Gb/s DS dicode signal has little power from DC to 1.2 GHz, so there is small overlap between it and the 2.5 Gb/s US NRZ signal shown by the spectrum of US seeded by cw light. This overlap becomes even less if the uplink is operated at lower speed. Fig. 10 also confirms that most of the residual DS signal in the US signal can be filtered out by the 2.7 GHz LPF (note that a narrower LPF could provide better results) since the DS signal power is concentrated within the frequency band of 2–5 GHz. On the contrary, it is obvious that the US signal seeded by the DS NRZ signal contains considerable amount of residual DS signal, especially at low frequencies near dc.

In the λ-reused system, the ER_d is a critical parameter since it significantly affects the performance of both up- and downlink. We measured the BERs of up- and downlink as a function of ER_d, and the results are given in Fig. 11. Due to the storage limit of the oscilloscope, the DS BERs cannot be measured below 2×10^{-7}. The power levels of the received DS and US signals are fixed to -23 and -20 dBm, respectively. The results obtained by the proposed scheme are compared with those acquired in the absence of CL coding. The DS BERs increase dramatically when the ER_d is smaller than 4 dB. On the other hand, if the ER_d is increased to over 4 dB, the US BERs increase drastically owing to the remodulation noise. It is apparent from Fig. 11 that replacing NRZ format with dicode format in the downlink achieves a 4 dB improvement in ER_d tolerance around the BER of 10^{-6} in the uplink, with only small penalty on the DS performance. The proposed system exhibits a stable performance in a wide range of ER_d, and alleviates the difficulties of accurate ER_d control. The eye diagrams of the back-to-back (b2b) US signals at the ER_d of 5 dB with and without the LPF using dicode or NRZ signal as the seed light are compared in Fig. 12. It is shown that the quality of the US signal is greatly improved by putting the 2.7 GHz LPF at the receiver for both DS dicode and NRZ seed signals. With the use of the LPF, larger eye opening of the US seeded by the dicode signal compared to that seeded by the NRZ signal proves the superiority of the proposed technique. Fig. 13 compares the US BERs as functions of ER_u at the fixed ER_d of 5 dB for the systems with and without level coding. Since dicode coding lessens the DS interference, to maintain the same SNR, the ONU does not need to generate high signal amplitude which is usually not practical at the user side. The required ER_u is reduced by 4 dB at the BER of 5×10^{-4} using dicoce-coded modulation in DS.

Since applying dicode encoding in downlink increases the power budget by avoiding the need for ONU's gain saturation, the system reach can be extended. To verify dicode coding as a potential solution to long-reach network, we measure BERs against fiber length for both up- and downlink. The results are measured at the ER_d of 5 dB and are plotted in Fig. 14. In this experiment, the launched power from OLT is fixed to 6 dBm, and the received optical power is adjusted to -20 dBm for all signals. The circled points in Fig. 14 are estimated from SNRs since the storage capacity of the sampling oscilloscope is not adequate for low BER measurement. When the dicode encoding

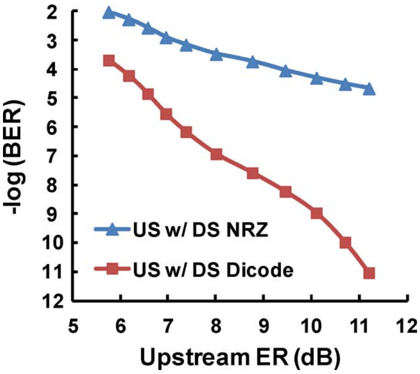

Fig. 13. BER of the uplink against the ER_u.

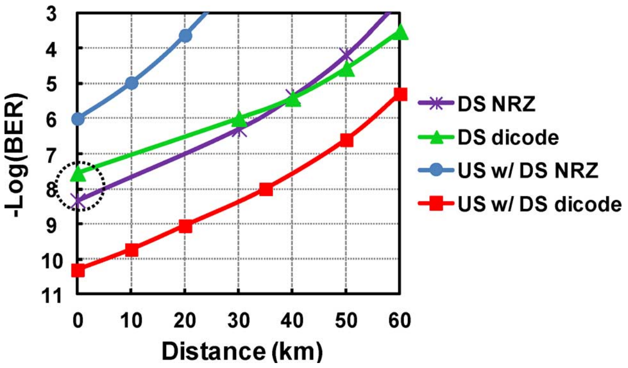

Fig. 14. BER versus transmission distance in wavelength-reused WDM-PON.

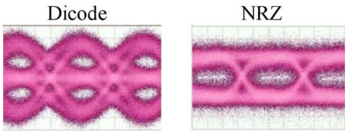

Fig. 15. Eye diagrams of DS signals after 60 km transmission.

is removed from the downlink, the maximal system reach for BERs below 5×10^{-4} is only 20 km, considering both DS and US directions. In contrast, by replacing NRZ signal with dicode signal in the downlink, 60 km bidirectional transmissions can be achieved without amplification and dispersion compensation at BERs below 5×10^{-4}. The proposed technique can also improve the RB tolerance by moving the spectrum of DS and US signals apart to minimize the crosstalk between them. Therefore, the dicode encoding is able to improve the performance of long-distance DS transmission suffering from the accumulated RB noise. As shown by the BER curves in Fig. 14, when the fiber length increases to over 40 km, the DS dicode signal starts to outperform the DS NRZ signal thanks to the capability of dicode encoding in the mitigation of Rayleigh noise. Fig. 15 gives the eye diagrams of the DS signal received after 60 km fiber in the format of dicode and NRZ and reveals the clearer dicode eye.

To evaluate the resilience to reflection noise in the uplink, we use the experimental setup shown in Fig. 16. The lower branch simulates the reflected DS signal as the crosstalk to US signal. For study on downlink reflection tolerance, the setup is evolved by disconnecting the fiber at point “b” after the PC to be connected at point “a,” while the link after the coupler at point “a” is connected to the coupler at point “b.” In this case, the generated US signal in the upper branch becomes the crosstalk to DS signal. Under the same parameters used for the experimental results in Fig. 11, the BERs given in Fig. 17 are measured by sweeping the CSR for both up- and downlinks. The ER_d is fixed to 5 dB for DS transmissions, while it is set to 4.5 and 7.5 dB for US transmissions seeded by NRZ signal and dicode signal, respectively. The BER curves confirm that the dicode level coding method improves the reflection tolerance by 4.5 and 5 dB in DS and US directions at BER of 3×10^{-4} and 10^{-6}, respectively, compared to the results obtained without using dicode coding.

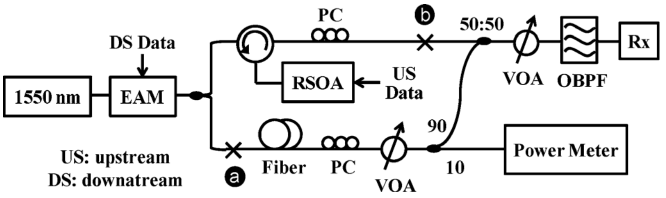

Fig. 16. Experimental setup for reflection tolerance study in wavelength-reused WDM-PON.

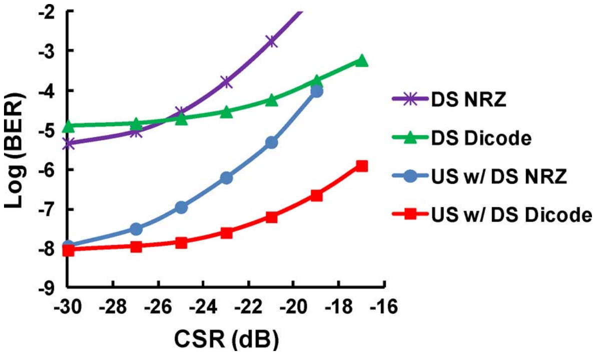

Fig. 17. BER versus CSR in wavelength-reused WDM-PON.

IV. CONCLUSION

In this paper, we have presented a cost-effective technique to mitigate the reflection noise in WDM-PON based on RSOA and centralized light generation. The proposed dicode coding with small complexity enables spectral shaping and adds no overhead. We apply dicode-coded modulation in the uplink of the WDM-PON with DS cw seed light or in the downlink of the WDM-PON with remodulated US signal. In the first case, the system’s reflection tolerance is substantially enhanced via the dicode-coded modulation in the uplink. Moreover, the system reach is extended by 15 and 25 km for data rate of 2.5 and 1.25 Gb/s, respectively. In the case of 1.25 Gb/s data rate, the tolerance to cw light reflection is improved by 6.5 dB at the BER of 5×10^{-5}, compared with NRZ modulation. In the second case, a 60 km full-duplex WDM-PON with 10 Gb/s dicode-coded downlink and 2.5 Gb/s remodulated uplink is demonstrated with great robustness against remodulation noise and reflection noise. The proposed technique greatly improves the US performance and achieves 4 dB more tolerance to ER_d.

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