SOA Assisted Wavelength Reusing for 25G Colorless PON With Low-Cost 10G EAM

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***Abstract*—This paper demonstrates a C-band 25G colorless passive optical network (PON) based on semiconductor optical amplifier (SOA) and 10G electro-absorption modulator (EAM). The experimental results show that the SOA in the optical network unit (ONU) can erase the downlink signal by taking advantage of the gain saturation feature, realizing the reuse of downstream wavelength. Meanwhile, the SOA gain can compensate for the EAM loss by optimizing the current and injection power. Apart from this, equalization algorithms at the optical line terminal are investigated for linear and nonlinear impairments compensation. Besides, the system robustness to the ASE and the maximum transmission speed are also evaluated. Finally, the system capacity can reach up to 25 Gbps with NRZ format at a bit-error ratio threshold of 2×10^{-2}, proving that this system is a promising technology for future high-speed colorless $2 \times$ 25G or $4 \times$ 25G Wavelength division Multiplexing (WDM) PON system.**

***Index Terms*—Passive optical network, wavelength reuse, DSP, colorless, SOA, EAM.**

I. Introduction

HIGH throughput applications such as 4k/8k video, augmented reality (AR), blockchain technology, and the internet of things are proliferating, which call for the upgrade of passive optical networks (PONs) capacity from 25 Gb/s and beyond [1]–[5]. PONs are often referred to as the last mile between an Internet service provider and the end customer. Since it's directly paid by users, it's cost-sensitive. Different strategies are proposed to reduce the system cost. Colorless optical network units (ONU) is the one solution. The implementation of colorless ONU can achieve wavelength adaption for Wavelength Division Multiplexing (WDM) PON. Then operators do not need to customize lasers with specific output wavelengths for each user, thus greatly cutting the operation and maintenance costs. A cost-effective colorless light source or tunable transmitter is indispensable for plug-and-play ONU. There are two commonly used colorless light sources: tunable lasers [6]–[8] and downstream light source reuse [9]–[11]. Tunable lasers have high bandwidth, simple structure, and strong wavelength configurability, but it is expensive since wavelength management and automatic calibration technology are needed. Wavelength reuse colorless ONU reflects and re-modulates optical carrier generated at optical line terminal (OLT). These schemes utilize identical wavelength for both upstream and downstream transmission, saving system resources and benefiting the maintenance and management of a centralized system. It has a cost advantage and is chosen as our colorless ONU scheme. 25G PON is the first step for the IEEE NG-EPON, two wavelength and even four wavelengths multiplexing for 50G and 100G PON are also widely discussed. Employing tunable lasers like proposed in NG-PON2 can meet this requirement, but the wavelength management in OLT is also difficult and increase the cost, which is why NG-PON2 would be skipped for real-deployment. So instead of using tunable laser, wavelength reusing would be a promising technology to meet the colorless requirement in the 50G and 100G WDM PON.

Recently proposed wavelength reuse methods are injection-locked Fabry Perot Laser Diode (FPLD) [12], directly modulated reflective semiconductor optical amplifier (RSOA) [13], [14], and external modulated semiconductor optical amplifier-reflective electro-absorption modulators (SOA-REAM) [15]. Injection-locked FPLD can amplify the optical signal and ensure the power budget of upstream data. But this scheme has a low transmission rate and poor chromatic dispersion (CD) tolerance. RSOA has low bandwidth and cannot support high-speed 25 Gbps signal transmission. Hence SOA-REAM is the promising technology for high-speed color-less transmission. Since integrated SOA-REAM is not available in our laboratory at the time of the experiment, the alternative scheme uses a circulator as a reflective device together with a SOA and EAM. The SOA erase downstream signal, generating the upstream carrier [16], and the EAM remodulate the carrier with the upstream signal.

Alternative, reusing legacy off-and-shelf 10G optics can also reduce the deployment cost which is preferrable by the vendors. But the bandwidth of 10G components is not enough for 25G signal transmission. Apart from that, SOA reduces partial interference introduced by downstream signal, there are still various

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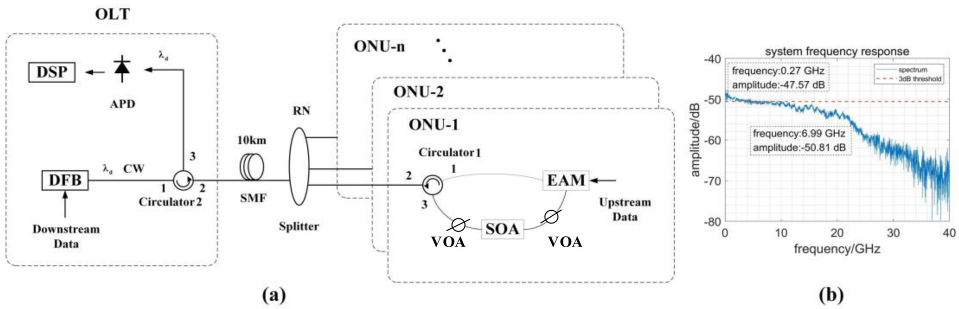

Fig. 1. (a) Experimental setup of 25G wavelength reuse system based on SOA-EAM and electrical equalizer. (b) Measured frequency response of the system.

impairments in the system, including linear impairment e.g., CD, and nonlinear impairment e.g., nonlinear response from optics. Digital signal processing (DSP) in the electrical domain is an efficient tool to mitigate these impairments comprehensively. In this work, wavelength reuse scheme based on low-cost 10G EAM and SOA is demonstrated, achieving 25 Gb/s upstream transmission. The structure of the 25G PON experiment setup is first introduced. Then, the linear and nonlinear impairments in the system is analyzed followed by an investigation of the equalization algorithms. The SOA gain saturation characteristics and avalanche photodiode (APD) sensitivity are also explored. Finally, the transmission performance and the noise robustness of our proposed scheme are evaluated.

II. Experiment Setup and System Impairment

The proposed loopback scheme based on SOA-EAM and DSP is shown in Fig. 1. On the OLT side, the 50 Gbps PAM4 downstream data is generated by 120 GSa/s Keysight M8194A arbitrary waveform generator (AWG) and directly modulated by a distributed feedback laser (DFB) with a central wavelength of 1550 nm.

Then the signal is fed into the 10 km standard single-mode fiber (SSMF) with an insertion loss of 0.2 dB/km and a dispersion coefficient of 16.75 ps/(nm*km). On the ONU side, an optical attenuator is used to tune the signal power to -11 dbm, which is within the SOA (THORLABS, BOA1004P) saturation regime. Inside the SOA, the signal power can be amplified while the downstream data is squeezed out simultaneously due to the SOA gain-saturation. Therefore, the signal after SOA can be reused for upstream carrier. In the upstream, the 25 Gbps non-return-to-zero (NRZ) signal is loaded onto the optical carrier by an EAM (Realphoton, EAM-40-S-FA-M) with a 3 dB bandwidth of 7 GHz. After fiber transmission, the upstream signal is received by an APD achieving optical to electrical conversion. Then the signal is sampled and offline processed with DSP. The optical circulators in both OLT and ONU are used for the separation of downstream and upstream signal.

The SOA+EAM approach benefits from wavelength flexibility avoiding the using of a costly tunable laser, which is cost-effective for upstream PON application. Nevertheless, there are some impairments in the system which degrade the signal quality such as the bandwidth limitation, CD, Rayleigh scattering, and reflective oscillation. These challenges are required to be investigated for its application in real deployment.

NRZ format with a high noise margin is adopted for uplink signal. The effective signal bandwidth of 25 Gbps NRZ signal is 12.5 GHz, larger than the bandwidth of the system spectrum. The limited bandwidth of the device will give rise to signal "trailing" and cause inter-symbol interference (ISI). Therefore, for the system electrical bandwidth, the narrower of the system bandwidth, the higher of the bit error ratio (BER) after system transmission. CD from fiber introduces a power fading effect in the spectrum causing pulse spreading and ISI [17]. CD can be easily compensated under coherent detection with an analytical formula because it is linear impairment and phase information is preserved. However, our system is a self-beating direct detection system and only amplitude information is extracted. Due to PD's square law detection, CD becomes nonlinear distortion and has a powerful effect on our signal. Moreover, all wavelength reuse bidirectional fiber systems have the problem of Rayleigh backscattered noise. Downstream signal's backscattered noise could mix with the upstream signal, and such in-band noise are hard to mitigate. Finally, reflective oscillation caused by the light leakage from the circulator leads to waveform fluctuation. Reflective oscillation is likewise a tough issue in this system. All these distortions can mix together, which further deteriorates the signal quality during transmission.

These are substantial impairments in the proposed high-speed optical communication system. Advanced DSP technology is a prevalent choice to enhance performance while maintaining low costs. Commonly used DSP equalization algorithms are feed-forward equalizer (FFE) [18]–[20] and Volterra equalizer (Vol)[21]–[22], which are the foundation of many state-of-the-art equalization approaches. The FFE is the transversal filter, and it can equalize linear damage. Vol based on contraction mappings and formulated in a general Banach space setting can equalize nonlinear effect[23]. FFE is powerful enough to deal with linear distortion such as bandwidth and CD. As introduced before, bandwidth limitation and CD can interact with the nonlinearities of the optical devices and make system impairment more complicated. Vol has a more satisfying performance than FFE but at the cost of higher computation complexity.

III. System Performance Analysis

A. SOA Gain Saturation Characteristics

The main function of the SOA in the setup is to erase the downstream PAM-4 signal, generating the optical carrier for uplink transmission. Thanks to the increased optical power, the

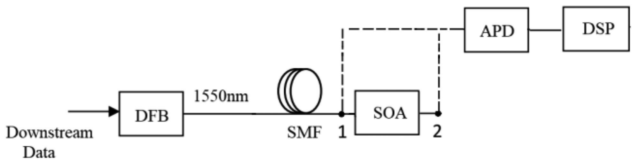

Fig. 2. Experimental validation of signal compression by SOA.

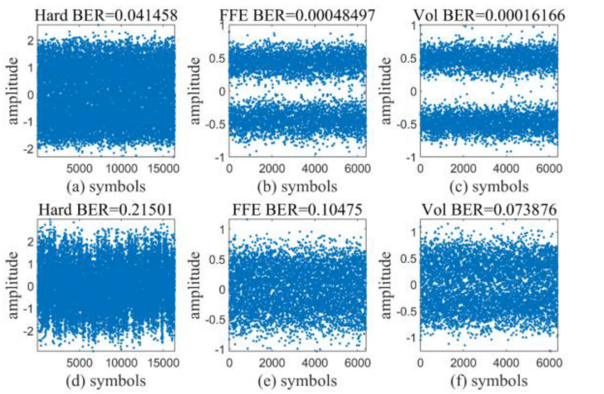

Fig. 3. Amplitude distribution and BER of the signal before and after SOA under (a), (d) hard decision, (b), (e) FFE algorithm, and (c), (f) Vol algorithm.

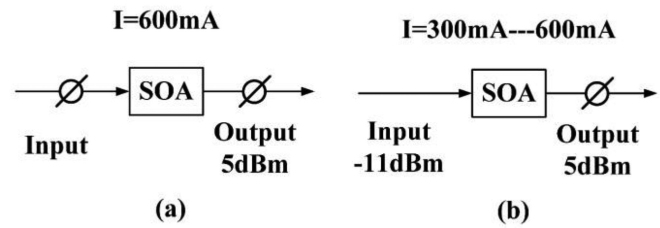

Fig. 4. (a) SOA input power optimization schematic. (b) SOA operating current optimization schematic.

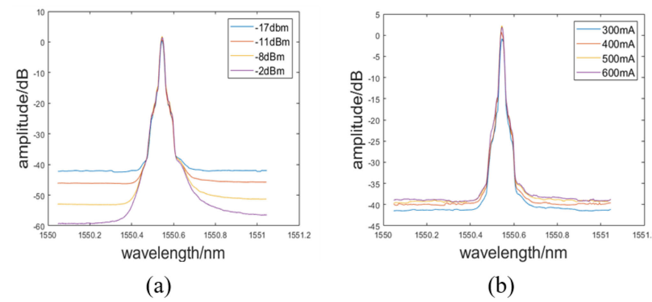

Fig. 5. (a) SOA output signal spectrum of different input power. (b) SOA output signal spectrum of different operating current.

EAM insertion loss can be compensated and the system power budget can be improved. Besides, a negative chirp is induced during SOA amplification, which counteracts the positive chirp from EAM modulation. Specifically, the SOA gain varies with symbols amplitude due to the gain saturation characteristic, e.g.,'0' symbols can have more power gain than '1' symbols. After amplification, the amplitude of '0' symbols is similar to that of the '1' symbols, leading to the suppression of the modulated signal. To verify this effect, the BER of the downstream signal with and without SOA is tested. The results are shown in Fig. 2. 50G PAM-4 is transmitted and the signal is extracted before SOA (marked as point 1) and after SOA (marked as point 2), respectively.

The amplitude distribution and BER before and after SOA are shown in Fig. 3. Both FFE and Vol algorithms have been optimized with taps. Here, only 6384 symbols are used for BER calculated, therefore the optimal BER is around 1.6×10^{-4} (1/6384). Due to the bandwidth limitation of the system without the SOA, the performance of hard decision is not accurate. After adding the equalization of FFE and Volterra algorithm, the performance becomes accurate. Among them, Volterra algorithm has the advantage in nonlinear compensation, so it performs the best performance. After adding SOA, the BER under Vol algorithms increases from 1.6×10^{-4} to 7.4×10^{-2}, indicating that the downstream signal is partially compressed, and the residual part may interfere with the upstream signal.

B. SOA Parameter Optimization

To obtain the optimal signal compression and also obtain enough power gain, the SOA working status needs to be optimized. SOA relative noise is determined by the SOA gain and input optical power, a performance measurement under different SOA working status is conducted. The test schematic is shown in Fig. 4. First the input power is investigated. In Fig. 4(a), the SOA operating current is set to 600 mA, the input power increases from −17 dBm to −2 dBm, and the output power is adjusted to 5 dBm for performance measurement. The optical spectrum of the SOA output signal shown in Fig. 5(a). It can be observed that the higher of the input power, the larger of the optical signal-to-noise ratio (OSNR). The reason is that the noise power is certain and output power standardizes. To achieve signal compression, the input signal power should be kept at a lower level resulting a lower OSNR of output signal. However, if the input power is too small, the output power cannot reach the expected value, leading to the decrease of system power budget.

For comprehensive consideration, −11 dBm is preferred.

After fixing the input power to −11 dBm, then we optimize the operating current. The operating current is increased from 300 mA to 600 mA at a scale of 100 mA, shown in Fig. 4(b). The noise power increases with the increase of current leading to a degraded OSNR. Meanwhile, a large current can provide a higher SOA gain. Therefore, to achieve effective signal compression, an operating current of 600 mA with a gain of 25 dB is selected for SOA in the experiment.

C. Sensitivity

Sensitivity is also tested and the result is depicted in Fig. 6. The received power varies from −17 dBm to −5 dBm with the step of 2 dBm. The input power to the APD is required to be set within this operating range, ensuring the stability of the system. With the BER threshold of 2×10^{-2}, the minimum receiving power of APD is −17 dBm. Considering the launching power is 5 dBm, so the power budget of the system can reach 22 dB satisfying the PR-10 power budget requirement. It can be optimized in several

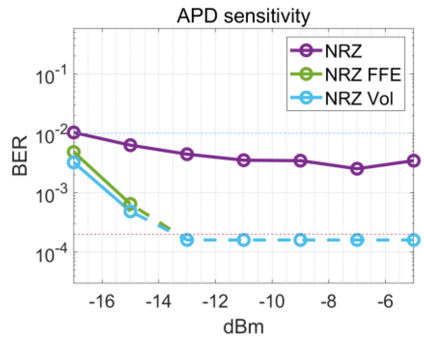

Fig. 6. Receiver sensitivity of 50 Gbps NRZ.

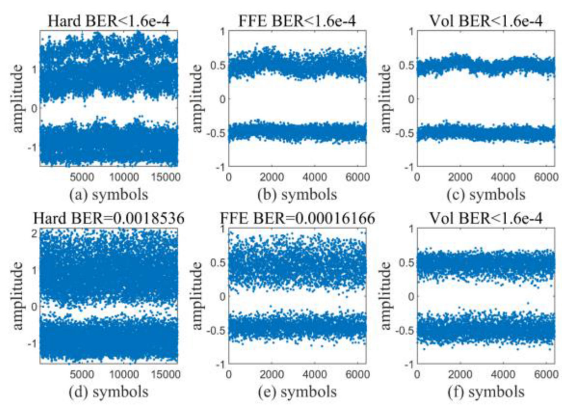

Fig. 7. Amplitude distribution and BER of single fiber unidirectional transmission system with 25G NRZ upstream signal under different algorithms: (a) Hard decision, (b) FFE algorithm, (c) Vol algorithm. Amplitude distribution and BER of single fiber unidirectional transmission system with 25G NRZ upstream signal and 50G PAM4 downstream signal under different algorithms: (d) Hard decision, (e) FFE algorithm, (f) Vol algorithm.

ways: (1) SOA with a gain of 30 dB can be selected, then the power budget of the system can reach 27 dB fulfilling the PR-20 power budget requirement. (2) Since the cost in OLT can be shared by all ONUs, using another SOA before the APD in the OLT to further increase the receiver sensitivity is possible, then PR-30 power budget could be achieved.

IV. Result and Analysis

A. The Waveform Comparison Between Unidirectional and Bidirectional System

The system transmission performance is investigated under two situations, namely unidirectional and bidirectional transmission. In the unidirectional transmission, only upstream 25 Gbps NRZ signal is transmitted, while both upstream 25 Gbps NRZ and downstream 50 Gbps PAM4 signal are transmitted in the bidirectional transmission. For the first case, the power launched into the circulator1 is 4 dBm. After fiber transmission, the signal is detected by an APD and BER is calculated offline. The amplitude distribution after the hard decision, FFE, and Vol algorithms are shown in Fig. 7(a)–(c). The interval between two amplitude level is easy to be distinguished after Vol equalization, and it is followed by FFE. Hard decision has the smallest interval since the system linear and nonlinear impairments are

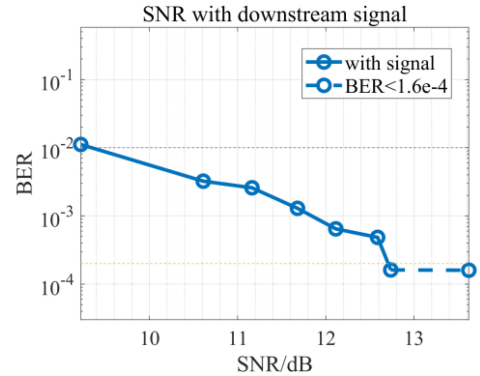

Fig. 8. The relationship between different SNR and BER for bidirectional transmission system.

not compensated. All BER is less than 1.6×10^{-4}. The system transmission quality is stable with a low BER. Moreover, the Rayleigh scattering and reflection of the optical circulator give rise to the signal jitter, and the signal level noise distribution variance is reduced following the equalization of the algorithm.

For the bidirectional situation, the overall transmission performance is degraded. Considering the downstream signal can only be partially erased by SOA gain saturation characteristic, the residual downstream signal may deteriorates upstream signal quality. The experimental results are displayed in Fig. 7(d)–(f). It can be observed that the interval between ‘0’ and ‘1’symbol level becomes smaller. Signal jitter still exists, but it is masked by the downstream signal becoming a negligible interference. The BER of hard decision, FFE, and Vol are 0.0018536, 0.00016166, and 1.6×10^{-4} (1/6384), respectively. Although the BER of this case is slightly inferior compared to the unidirectional case, it is still lower than the required threshold of 2×10^{-4}. After this comparison, we can conclude that DSP algorithms can equalize bandwidth limitation and part of nonlinearity.

B. System Noise Robustness Evaluation

Then the system robustness to the noise is tested. After synchronization, resampling, and eliminating bandwidth limitation through the Vol algorithm, SNR of the received data is estimated by a method named error vector magnitude, which is accurate if the received optical field is only AWGN interference. As illustrated in Fig. 8, SNR is 12.74 dB with 2×10^{-4} BER threshold and 9.22 dB with 2×10^{-2} BER threshold. This SNR is low and represents system fine noise robustness.

C. System Transmission Rate

To explore the highest data transmission rate of the unidirectional and bidirectional transmission system, the system rate is swept in the range of 20 Gbaud −50 Gbaud with the step of 5 Gbaud. As shown in Figs. 9 and 10, the increased transmission rate causes all BERs rise rapidly even with equalizers. This is because with the increase of rate, signal bandwidth becomes wider and system bandwidth has a stronger effect on the signal. Equalization algorithms can slightly slow the growth of BER but cannot completely suppress it.

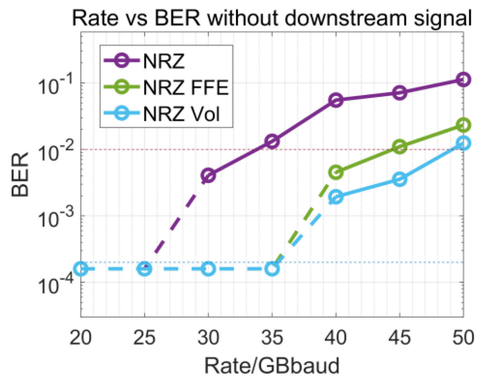

Fig. 9. The relationship between different rate and BER for unidirectional transmission system.

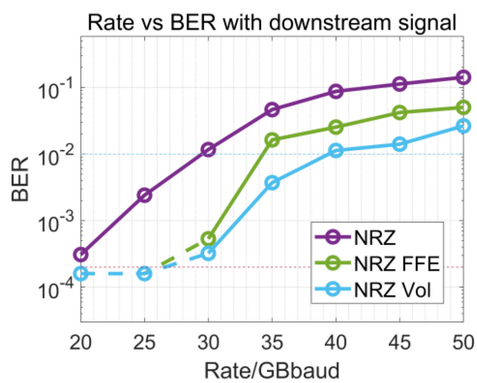

Fig. 10. The relationship between different rate and BER for bidirectional transmission system.

For the unidirectional transmission system, the transmission speed reaches up to 45 Gbaud with the BER threshold of 1×10^{-2} and 35 Gbaud with the threshold of 2×10^{-4}. For the bidirectional transmission system, the hard decision BER at 35 Gbaud is 1.32×10^{-2}, which is beyond the 1×10^{-2} threshold. After the Vol equalization, the BER at 35 Gbaud can be reduced to 1.94×10^{-3}. The speed reaches 35 Gbaud with the BER threshold of 2×10^{-4} and 25 Gbaud with the BER threshold of 2×10^{-4}.

V. Conclusion

In conclusion, the system proposed realizes 25G low-cost and high-performance PON. By utilizing the wavelength reuse technology, the optical carrier of OLT DFB laser can be reused. Therefore there is no need to add another light source for uplink signal, reducing the use of tunable lasers and saving the system cost. The SOA+EAM structure is adopted, which can effectively compensate for the insertion loss generated by EAM as the gain of SOA increases. The use of 10G bandwidth-limited EAM further reduces the cost of the system, and various signal equalization algorithms compensate for the bandwidth limitations of the device. By analyzing the system BER, both the FFE algorithm and VOL algorithm can improve the system performance, and the VOL algorithm outperforms FFE. The test demonstrates that the system has a strong anti-interference ability and satisfactory noise robustness. With the 2×10^{-4} BER threshold and the 10 km fiber transmission, the rate of the single-fiber unidirectional transmission system and the single-fiber bidirectional system can reach 35 Gbps and 25 Gbps, respectively, under the VOL algorithm equalization.

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