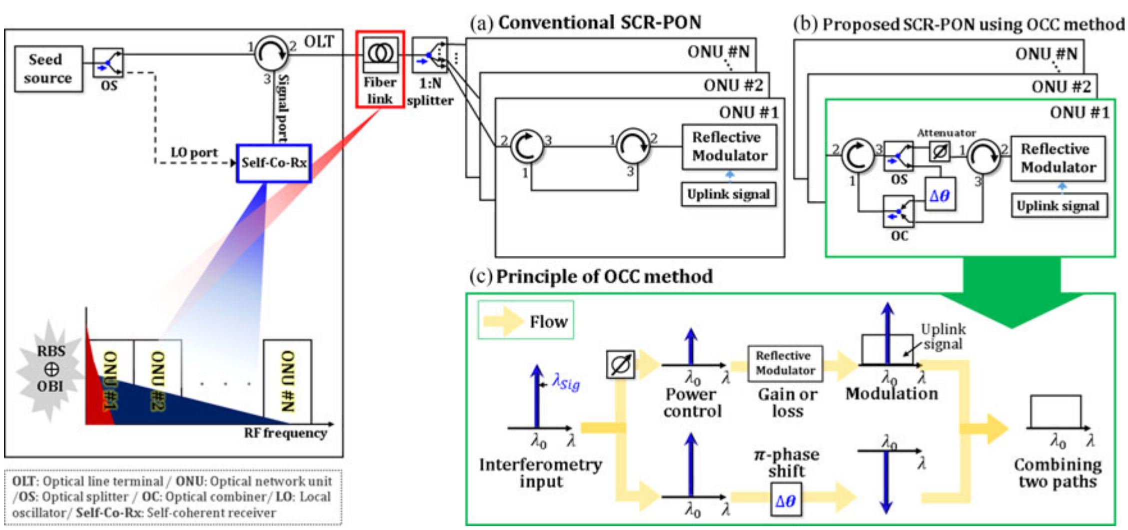
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Mitigation of Optical Interference Noise by Optical Carrier Cancelation in Self-Coherent Reflective PON Uplink Transmission

Volume 9, Number 3, June 2017

Soo-Min Kang
Kyoung-Hak Mun
Sang-Min Jung
Sang-Kook Han, *Senior Member, IEEE*



DOI: 10.1109/JPHOT.2017.2698079
1943-0655 © 2017 IEEE

Mitigation of Optical Interference Noise by Optical Carrier Cancelation in Self-Coherent Reflective PON Uplink Transmission

Soo-Min Kang, Kyoung-Hak Mun, Sang-Min Jung, and Sang-Kook Han, ***Senior Member, IEEE***

Department of Electrical and Electronic Engineering, Yonsei University, Seoul 07322, South Korea

DOI:10.1109/JPHOT.2017.2698079
1943-0655 © 2017 IEEE. Translations and content mining are permitted for academic research only. Personal use is also permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

Manuscript received March 30, 2017; accepted April 23, 2017. Date of publication April 26, 2017; date of current version May 4, 2017. This work was supported by the ICT R&D program of MSIP/IITP, South Korea [B0101-17-0131, Next-generation coherent optical access physical network]. Corresponding author: S.-K. Han (e-mail: skhan@yonsei.ac.kr).

Abstract: Optical interference noise (OIN), including optical beating interference and Rayleigh back-scattering noise, severely degrades transmission performance in self-coherent reflective passive optical network uplink transmission systems. A simple, cost-effective, and optical interferometry-based optical carrier cancelation method is proposed to reduce OIN. In this experiment, we demonstrate the cancelation of optical carriers, which is a major cause of OIN, up to 29 dB. Under the conditions of higher fiber input power and longer transmission distance, a remarkable improvement in transmission performance in terms of the eye-pattern and bit-error-rate was achieved.

Index Terms: Optical fiber communication, multiple access interference, optical interferometry.

1. Introduction

Data traffic is rapidly increasing in passive optical networks (PONs) due to the advances in various applications of wireless, wired, and internet of things (IoT) services. Moreover, the need for a higher splitting ratio and longer transmission distance will be intensified for the future PONs [1]. Among the various candidates meeting these requirements, coherent PON is a potential solution, demonstrating high spectral efficiency (SE) and receiver sensitivity [2]. However, unlike most long-haul and point-to-point coherent transmission systems, unavoidable multiple carrier frequency offset (CFO) and phase noise (PN), occur in each optical network unit (ONU), should be considered in the multiple access in coherent PON [3]–[5]. CFO occurs between the transmitter and the local oscillator (LO). It is related to the stability of the laser and may interfere with the received signal [3], [4]. In addition, PN is due to laser linewidth and becomes larger with wider linewidth [5]. This PN also perturbs the signal and degrades transmission performance. As the number of ONUs increases with splitting ratio and transmission distance, these problems will be aggravated. To avoid such problems, lasers with both narrow linewidths and high stability are required, imposing a cost burden on each ONU and requiring complex compensation techniques to mitigate multiple-CFO and PN.

To deal with the inevitable drawbacks mentioned above, the self-coherent reflective PON (SCR-PON) system was reported [6]–[8]. Its basic structure consists of a reflective modulator based ONU and a self-coherent detection-based optical line terminal (OLT). In this system, the unmodulated uplink wavelength from the OLT is seeded into each ONU, and the uplink signal is modulated through the reflective modulator. In [6], it is noted that various optical devices, such as reflective semi-conductor optical amplifiers (RSOAs), reflective-electro-absorption modulators (R-EAMs), and other more advanced technologies, can be implemented in the ONU. In particular, because optical gain of RSOA is high, RSOA-based SCR-PON is a promising candidate for retaining the high power budget for high splitting ratio and long transmission distance. Since this simple structure avoids a costly optical source in the SCR-PON system, it is a more cost-effective system as compared with the conventional coherent PON system shown in [2]. At the OLT, high receiver sensitivity can be provided due to self-coherent detection. In addition, SCR-PON does not require a laser source as the LO at the coherent receiver (Co-Rx) and for complex compensation techniques to address multiple-CFO and PN.

However, two major optical-interference-noise (OIN) sources remain critical issues that can severely degrade the transmission performance in an SCR-PON uplink transmission system. One is optical beating interference (OBI) noise, and the other is Rayleigh back scattering (RBS) noise. OBI noise is an optical beating term based on the square-law detection in the photodetector [9]. It is generated by the uplink DC carrier-to-LO carrier beat at the Co-Rx, and can affect the beat components of uplink signal-to-LO carrier at the same receiver. It is unwanted components throughout the whole frequency band as it interferes with the uplink signal. RBS noise is a linearly back-scattered component arising from fiber non-uniformity in a single-fiber loopback system [10], [11]. The influence of the RBS noise is more severe under high fiber input power, narrow laser linewidth, and long transmission distance. Moreover, noise power of the RBS becomes stronger when the uplink transmission is performed in a single-fiber loopback system. Since the RBS noise is also mainly generated from the high power of the optical carrier during single-fiber loopback at the fiber link, both OIN sources become major obstacles in the SCR-PON uplink transmission system, in which the optical carrier exists on the uplink signal.

Several solutions for the OIN have been proposed [9], [12]–[19]. To mitigate the OBI noise, various methods, such as bias control of an uplink intensity modulator [9], wavelength separation [12], polarization division multiplexing [13], and optical spectrum broadening using the out-of-signal band RF clipping tone [14] have been reported. However, difficulties with these methods include problems of adopting an expensive modulator at each ONU, wavelength waste by each ONU, the significant hardware complexity, and both bandwidth waste of the optical devices and weak tolerance to long-haul transmission. Methods such as subcarrier multiplexing (SCM) techniques [15], phase modulation through bias dithering [16], an optical high pass filter using the gain saturation property of a semi-conductor optical amplifier (SOA) [17], bias control of the optical external modulator [18], and optical spectrum broadening by using out-of-signal band RF clipping tone [19] have been proposed as solutions to the RBS noise. Nevertheless, the high system complexity with simultaneous bandwidth waste, weak tolerance for long-haul transmission due to the broadened linewidth, power burden in reaching the gain-saturation region of the SOA, the need for additional modulators, and both bandwidth waste and weak tolerance to long-haul transmission are limitations to the existing solutions. In addition, solutions to the OIN in the SCR-PON system have been reported using digital signal processing (DSP) [7], [8].

In this paper, a novel OIN reduction technique for an SCR-PON uplink transmission system is proposed. OIN generated by optical carriers at the ONU is reduced through an optical-carrier-cancelation (OCC) method. The proposed OCC method is based on generating destructive interference between two optical-interferometric paths at the ONU. The optical carrier was experimentally suppressed up to 29 dB in the uplink transmission, and the resulting OIN was effectively minimized. Remarkable performance improvement was demonstrated in terms of the bit-error ratio (BER) and eye-pattern measurements, which imply tolerance for OIN under a severely OIN-induced environment.

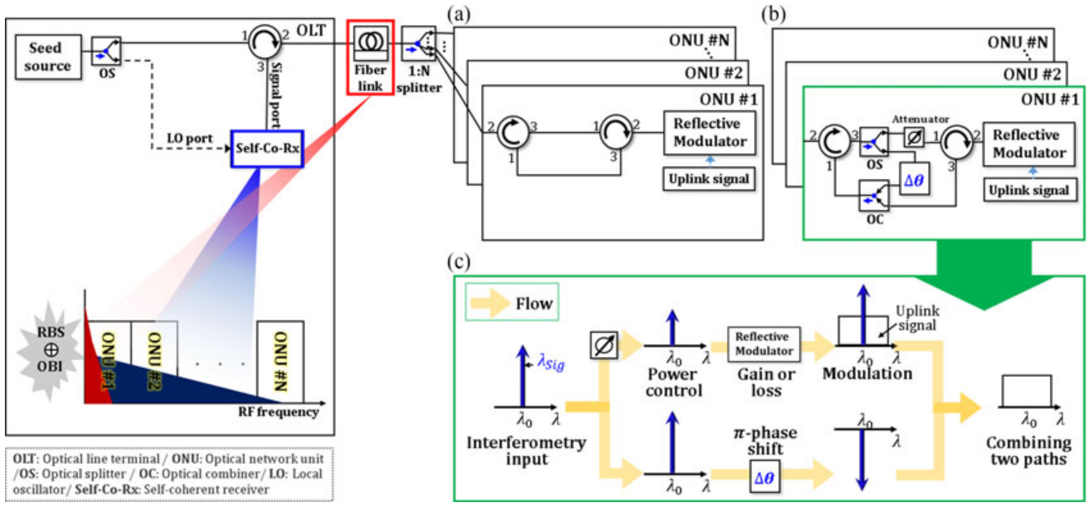


Fig. 1. Schematics of the (a) conventional SCR-PON uplink-transmission system. (b) Proposed SCR-PON uplink-transmission system using an OCC method and detailed process of (b).

2. Theoretical Approach

Fig. 1 illustrates the conventional SCR-PON uplink-transmission system with generation of the OIN, as well as the operating principle of the proposed system. In this paper, the conventional SCR-PON architecture is assumed to include a reflective modulator at the ONU and self-coherent detection at the OLT, as shown in [6]. Only an uplink-transmission system including an ONU is considered as a proof of the proposed concept. As shown in Fig. 1(a), an optical carrier from the seed source is divided into two optical paths via an optical splitter (OS) at the OLT. One of the carriers is induced into a fiber link and a 1:N splitter, where N is the total number of multiple-accessed ONUs. Another carrier enters the LO port of the Co-Rx and enables as a self-homodyne detection [6]–[8]. The uplink signal is modulated through the reflective modulator at the ONU and is received by the Co-Rx at the OLT.

In this environment, OIN including both OBI and RBS noise components inevitably occurs [9], [11]. First, the OBI noise arises from a carrier-to-carrier beat when more than two optical carriers are received at a photodetector. As derived theoretically in [9], the basic principle of coherent receiving is based on optical beating using the LO carrier. If the optical carrier of the uplink signal is not suppressed, it beats with the LO carrier at this receiver. Therefore, this beat component can interfere with the uplink signal-to-LO carrier beat and the uplink signal can be distorted. That is, unwanted beating terms are dispersed from the DC to the signal band and can interfere with the uplink signal. They become more severe with increasing optical-carrier power before the fiber link. Second, RBS noise is a linearly backscattered-component caused by non-uniformity of the fiber structure in the single-fiber loopback system [11]. Moreover, this carrier-induced reflection component can create beats with the LO carrier due to square-law detection at the Co-Rx. The RBS noise is concentrated near the DC (low-frequency) region with higher power as compared with the OBI noise whose power is dispersed overall-frequency region, as depicted in Fig. 1. Both the power and bandwidth of the RBS noise are increased for longer transmission distance, high optical-carrier powers, and narrow linewidths [10]. Since the optical carrier exists during the uplink-transmission, the OIN interferes with the uplink signal and degrades the transmission performance, as depicted in the RF spectrum of Fig. 1. Thus, if the optical carrier, which generates the OIN, could be canceled out, these problems could be solved. Therefore, a method of mitigating the OIN through cancelation of the optical carrier is important for this scheme.

The proposed system is depicted in Fig. 1(b) and (c). Fig. 1(b) depicts the OCC method based SCR-PON uplink system, and Fig. 1(c) illustrates the detailed process of Fig. 1(b). Our goal is to cancel out the optical carrier, which is a major cause of OIN. The proposed OCC method is based on simple optical interferometry consisting of two optical interferometric paths. The basic principle of the OCC method is to create destructive interference between two paths, through a π-phase difference. In Fig. 1(c), the optical-interferometry input is divided into two halves. One is controlled through a power-control device and induced into the reflective modulator with reflection gain or insertion loss; next, the uplink signal of frequency λ_0 is directly modulated. The second half undergoes a π-phase shift through the phase-control device. By combining these two carriers, destructive interference is generated and the carriers are canceled out. In the perfect OCC method, three key parameters should be considered: the phase, power, and polarization.

Firstly, an exact phase difference of π-radians between the two optical-interferometric paths should be implemented. The two paths are generated after the OS at the ONU, as shown in Fig. 1(b). One path is fed into the reflective modulator; the uplink signal is directly modulated on this carrier. The other path passes through optical components enabling phase variation. The purpose of generating these two paths is to cancel out the optical carrier using the π-phase difference between them (destructive interference), as depicted in Fig. 1(c). An optical phase shifter (OPS), specially customized optical delay line (ODL), optical tunable delay line (OTDL), and other components may be useful in creating destructive interference. The π-phase difference could be implemented by adjusting the DC bias of the OPS, the length of the ODL, or the tuning of the OTDL. Of these options, adoption of the OPS is recommended because of its low cost and easy tunability.

Secondly, optical-carrier power imbalance between the two paths should be minimized, as shown in Fig. 1(c). If the reflective modulator is applied to the ONU, there is reflection gain or insertion loss. For example, the R-EAM and the RSOA have insertion loss or reflective gain respectively. Depending on the ONU structures, the optical power between the two paths changes due to the gain or loss of these options. To minimize the optical power imbalance and retain a sufficient signal-to-noise ratio (SNR) of the uplink signal, a differential degree of optical power splitting in front of the interferometry or the insertion of a loss medium inside the interferometry can be performed. For example, OSs with different splitting ratios such as 1:9-, 2.5:7.5-splitters; gain mediums such as optical amplifiers; variable optical attenuators (VOAs); or loss media such as sufficiently long optical fibers may be helpful. A VOA before a reflective modulator would be a good solution for enabling flexible power attenuation and retaining the SNR of the modulated uplink signal at the same time.

Third, the state of polarization (SOP) between the two paths should be matched [20]. In optical interferometry that uses phase difference, matching the SOPs between the two optical interferometric paths is required for ideal and stable implementation. To control the SOPs, adoption of in-line polarization controllers (PCs), polarization-maintaining fibers (PMFs), or more advanced polarization stabilization techniques are suitable. These three considerations need to be satisfied for ideal OCC operation.

Assuming perfect matching of SOPs between two optical interferometric paths, let the input optical carrier in Fig. 1(b) be given by E(t). Then, the optical fields of each path can be given by

$$\frac{E(t)}{\sqrt{2}}\alpha G \tag{1}$$

$$\frac{E(t)}{\sqrt{2}}e^{j\theta} \tag{2}$$

$$E_{total}(t) = \frac{E(t)}{\sqrt{2}}(\alpha G + e^{j\theta}) \tag{3}$$

Equation (1) expresses the upper optical interferometric path shown in Fig. 1(c), where α is the degree of power attenuation in linear units and G is the reflection gain or insertion loss of the reflective modulator. Equation (2) shows the lower path depicted in Fig. 1(b), where θ is the phase difference in radians. If a 50:50 OS is used, the optical power is divided into two halves. Equation (3) shows the total optical field after the OCC method. If an exact phase difference of π-radians ($\theta = \pi$) is implemented and αG maximally equal to 1 is satisfied through the control of the optical power imbalance, the power of the total optical field may be made zero. Thus, the optical carrier would be

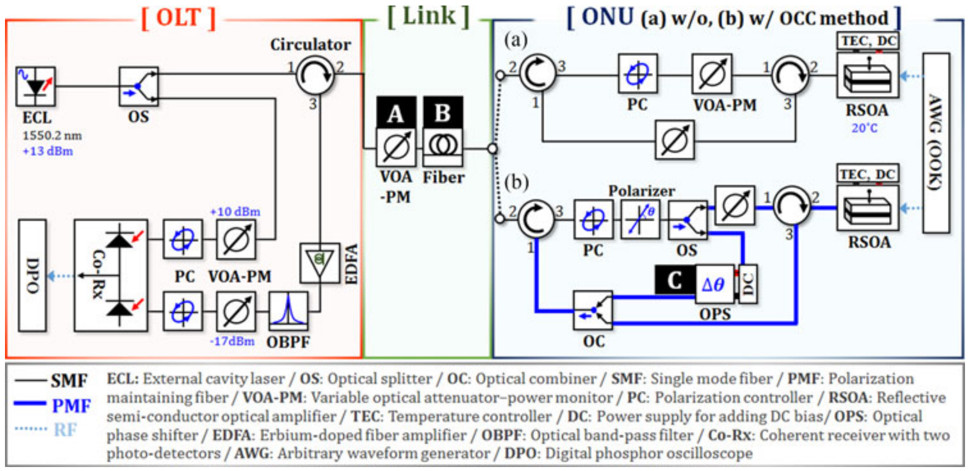


Fig. 2. Experimental setups for the comparison between the (a) conventional SCR-PON uplink-transmission system and (b) proposed SCR-PON uplink-transmission system.

perfectly canceled out. Moreover, in practice, the SOPs in optical interferometry should also match to ensure stable operation.

The proposed OCC method for reducing the OIN in the SCR-PON uplink transmission is a simple and cost-effective solution that does not require high-performance optical devices like optical band-pass/stop filters or external optical modulators, and does not waste resources such as wavelength or frequency. Since the proposed OCC method is applied after uplink-signal modulation, it also secures transparency for the modulation format. In addition, the proposed SCR-PON uplink transmission does not use additional DSP techniques for OIN reduction because it eliminates the cause of OIN at the uplink transmitter. Therefore, the proposed system can reduce OIN and thereby become a simple, cost-effective, and transparent modulation format.

3. Experimental Setup

Fig. 2 depicts the experimental setups for comparison between the conventional and proposed SCR-PON uplink systems. The operational principles of both SCR-PON systems are as shown in Fig. 1. Fig. 2(a) is the conventional SCR-PON, and Fig. 2(b) shows the proposed SCR-PON using the OCC method. This work focused only on uplink transmission.

At the OLT, an external cavity laser (ECL) with a center wavelength of 1550.2 nm was used as an optical seeding carrier with a fixed linewidth ($<$100 kHz). Two optical paths were generated by OS at the OLT. One was induced into the fiber link and reflected back from the reflective modulator at the ONU; then, it was sent back to the OLT through the transmission fiber. The other entered the LO port of the Co-Rx (100 Gbps DP-QPSK Co-Rx, Fujitsu FIM24706). The receiver sensitivity (@ BER $= 10^{-3}$) under the optical back-to-back condition was –33 dBm, and 25 Gbps of on-off keying (OOK) transmission was possible through this receiver. In the Co-Rx enabled for self-homodyne detection, two photodetectors were used for balanced detection. The SOPs and received optical powers of both the signal and the LO port were fixed using PCs and variable optical attenuator-power monitors (VOA-PM). In the ONU, in both cases as shown in Fig. 2(a) and (b), the RSOA was used as a reflective modulator to retain sufficient optical power for uplink transmission in both systems. The OOK uplink signal, which is a $2^{11} - 1$-bit single pseudo-random binary sequences (PRBS), including an electrical bandwidth of 1 GHz, was directly modulated to compare the characteristics of Fig. 2(a) and (b). To observe the improvement of the proposed system intensively in the low-frequency region, only the 1 GHz OOK signal was modulated as a proof of concept. This signal was used for investigation of the channel state in eye-pattern and bit-error-rate (BER) performance. In both Fig. 2(a) and (b), due to polarization-dependent property of the RSOA, a PC in front of it was

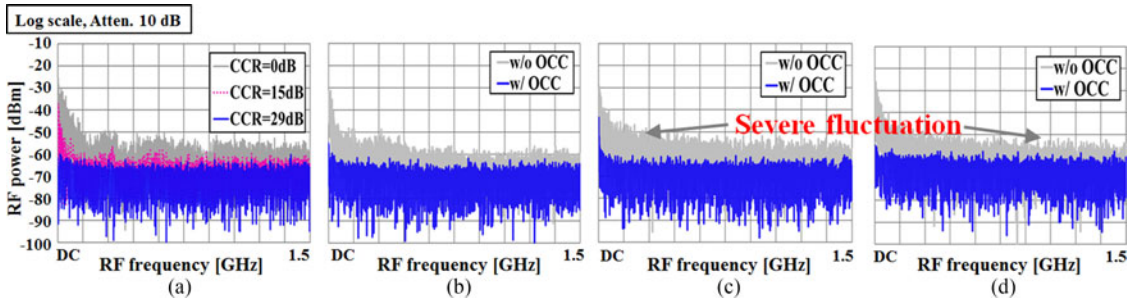


Fig. 3. RF noise floor according to the (a) CCR with fixed fiber input power of –1 dBm at 0 km and to the transmission distance of (a) 20, (b) 40, and (c) 60 km with fixed fiber input power of –4 dBm.

used to maximize the modulation efficiency. The RSOA was governed by a temperature controller (TEC) and DC power supply (20 °C, 60 mA). After coherent detection at the OLT, the received signal was captured by a digital phosphor oscilloscope (DPO, Tektronix 72004C) with 50G sample/s, and the transmission performance was evaluated by off-line processing. In this experiment, no additional DSP was used to reduce the OIN.

Three important parameters for the OCC method, as mentioned in Section 2 were optimized in Fig. 2(b). By adjusting the DC bias of the OPS (Phoenix Photonics, VPS-15) in optical interferometry, carrier cancelation up to a maximum of 29 dB was experimentally achieved. In addition, a short PMF (<0.5 m) was used to match the lengths of the two optical-interferometric paths, and VOAs were used to minimize the optical-power imbalance of each path. As a result, the power difference between each path was kept below 6 dB. The powers between the two paths were monitored regularly using a power monitor. To maintain the SOPs in optical interferometry, PMFs were used at both paths. In addition, the SOP of the linear polarization needed to be matched with the aligned axis of PMFs by using the PC and the linear polarizer before optical interferometry could be performed. We first obtained the linear polarization using the PC and polarizer. Then, the polarization extinction ratio (PER) was maximized by controlling the PC.

To compare both systems in the OIN-induced environment, two experiments were performed. The first checked the OCC performance according to the carrier-cancelation ratio (CCR) with fixed transmission distance to analyze the influence of the OBI noise only (CCR at a marked point C in Fig. 2 was varied while points of A and B were fixed). The second experiment measured performance by varying the fiber-input power at various transmission distances (the marked points A and B were varied while CCR at the point C was fixed). In this second measurement, the influence of OIN including both OBI and RBS noises was considered. These two experiments were performed one at a time. For a fair comparison, the optical power at the signal and the LO ports before the Co-Rx were fixed in both experiments as –17 dBm and +10 dBm, respectively, using an erbium-doped fiber amplifier (EDFA) and the VOA-PM. In addition, an optical bandpass filter (OBPF) was used to remove the amplified-spontaneous-emission noise.

4. Results and Discussion

The RF noise floor (NF) was observed before uplink-signal modulation; then, the uplink signal was modulated and transmission performances were measured.

Fig. 3 shows the NF of the conventional and proposed SCR-PON uplink-transmission systems. Based on the standard of NG-PON2 [1], [10], the minimum fiber-input power x was calculated using (4) [10].

$$x - 0.2L - 3\log_2 N \geq -25. \quad (4)$$

Here, *0.2*, *L*, *3*, and *N* are the typical single fiber loss in [dB/km], transmission distance in [km], typical optical splitter loss of the PON system [dB], and the number of multiple accessed ONUs. In

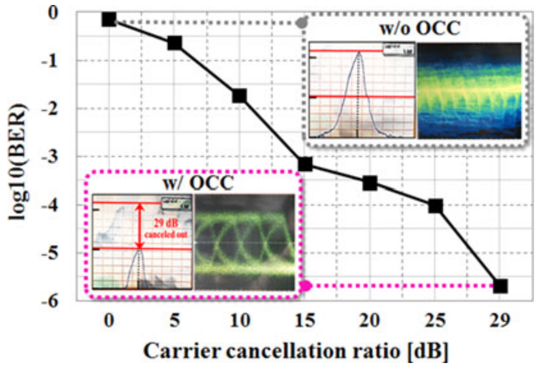


Fig. 4. BER performances according to the CCR. (Insets: optical spectra and eye-patterns).

addition, a minimum receiver sensitivity of –25 dBm for meeting NG-PON2 standard was assumed. At least –7, –4 and –1 dBm were needed for N values of 64, 128, and 256, respectively.

Based on (4), we fixed the fiber-input power of –1 dBm at 0 km, which was relevant to 256 ONUs. Firstly, Fig. 3(a) shows the influences of the CCR. At the optical back-to-back (0 km), the OBI noise could be generated from the carrier-to-carrier beat at the Co-Rx, as explained in Section 2. It was dispersed from the DC to the overall frequency band. When the CCR was zero, i.e., the case without the OCC method, the NF was seriously deteriorated. On the other hand, when the OCC method was applied, the NF was remarkably lowered and stabilized as the CCR increased. NF above 15 dB was reduced in the overall frequency band and especially in the DC region. In a practical-transmission environment, more power would be required because of insertion losses from various optical devices. Thus, more severe OBI noise could be generated in practice because this noise is proportional to the optical-carrier power [9].

In Fig. 3(b)–(d), transmission distance *L* was set to 20, 40, and 60 km, respectively. The optical power was fixed at –4 dBm to consider the influence of the OIN including both OBI and RBS noises by only varying the transmission distance. The severity of the OIN increased with increasing transmission distance [10], [11]. The RBS noise due to the reflected component of the optical carrier was concentrated in the DC region with high noise power as depicted in both the spectra. Moreover, this OIN severely fluctuated in time and frequency domains as transmission distance increased. As a result, the proposed OCC method was tolerant to OIN.

After the uplink signal was directly modulated by the RSOA, we firstly tested the OCC method with the OBI noise only and the transmission performances were then measured with various lengths of fiber. Sufficient digital samples of 1 GHz of the single PRBS signal were retained through repetitive transmission of this signal. For a fair performance comparison between the cases with and without the OCC method, additional optical processing or DSP techniques were not used. Fig. 4 depicts the BER performances according to the CCR. The insets of Fig. 4 depict the optical spectra and eye-patterns at the certain CCR. A fiber-input power of –1 dBm and a transmission distance of 0 km were fixed to only measure the influence of the OBI noise. In this case, the RBS noise was not considered. That is, CCR at a marked points of C in Fig. 2(b) was varied with fixed points of A and B. Among the many solutions used to generate an optical-phase difference between the two interferometric paths, in this paper, the OPS was used because it is cheaper and simple to control. Optical spectra were captured according to the DC bias of the OPS. When CCR was 0 dB, the constructive interference between two paths was achieved at the in-phase bias point. Both BER and the eye-pattern were severely degraded due to the OBI noise. OBI noise is inevitably generated because of carrier-to-carrier beat at the Co-Rx. However, when CCR was 29 dB, which was operated at the out-of-phase bias point, the destructive interference between two paths was generated. At that point, a maximal CCR of 29 dB was achieved. BER was remarkably improved and a clear eye-pattern was observed. During the experiment, the holding time of the OCC method was maintained up to tens of minutes. Although the SOP fluctuated slightly up to the second decimal

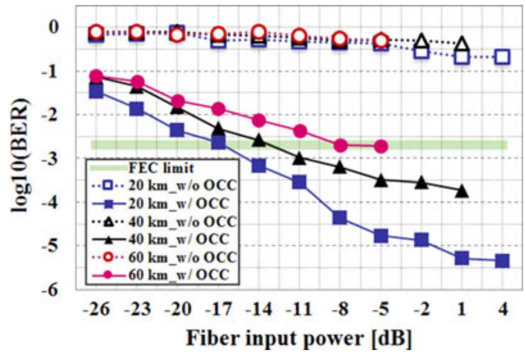


Fig. 5. BER performances according to the fiber input power at the different transmission distances.

place at that time, it could be stabilized sufficiently through the PC. These results, show that the optical carrier severely degraded performance, which was mitigated through the OCC method.

Fig. 5 depicts the BER results with various transmission distances. CCR at the point C in Fig. 2 was fixed and points of A and B were varied to measure the OIN, including both OBI and RBS noises. Optical distributed network loss was fixed at 30 dB to focus on OIN according to fiber-input power and transmission distance. Since the influence of the OIN, especially on the RBS noise, was directly related to the fiber-input power and transmission distance, we varied these two parameters in this experiment. When the OCC method was not applied, the BER results at all transmission distances were degraded such that the uplink signal could not be demodulated correctly. In addition, the performance was more severely degraded as the transmission distance was increased by the RBS noise, which was proportional to the launch power. On the other hand, with the OCC method, the performance was improved over the entire range of fiber input powers and transmission lengths. Sufficient BER performance under the FEC limit (2×10^{-3}) was acquired at long transmission distances up to 60 km with the sufficient fiber-input power. As a result, because the OCC method enabling avoidance of the OIN was applied to the uplink transmitter, transmission performance was sufficiently secured.

Consequently, the proposed method was able to reduce the OIN remarkably by preventing it at the uplink transmitter. This was achieved using a simple and cost-effective system, enabling retention of the power budget, transparency for modulation format, and tunability for use of multiple ONUs at the same time. For further improvement, a polarization stabilization technique using a simple real-time processor is needed at the ONU.

5. Conclusion

We proposed and demonstrated a novel SCR-PON uplink-transmission system using an OCC technique. A good tolerance for the OIN including both RBS and OBI noises was experimentally verified. The NF and BER performances and eye-pattern were successfully improved, even in the OIN-induced environment with a higher incident optical power and longer transmission length. The proposed system is a promising candidate for eliminating the severe OIN in SCR-PON systems with added benefits of cost-effectiveness and low-complexity.

References

[1] ITU-T G.989.1, 40-Gigabit-capable passive optical networks (NG-PON2): General requirements, Mar. 2013.
[2] K. Kikuchi, "Fundamentals of coherent optical fiber communications," *J. Lightw. Technol.*, vol. 34, no. 1, pp. 157–179, Jan. 2016.
[3] A. Shahpari *et al.*, "Coherent access: A review," *J. Lightw. Technol.*, vol. 35, no. 4, pp. 1050–1058, Feb. 2017.
[4] A. Meiyappan, P. Y. Kam, and H. Kim, "On decision aided carrier phase and frequency offset estimation in coherent optical receivers," *J. Lightw. Technol.*, vol. 31, no. 13, pp. 2055–2069, Jul. 2013.

[5] S. Camate and V. Ferrero, “Narrow linewidth CW laser phase noise characterization methods for coherent transmission system applications,” *J. Lightw. Technol.*, vol. 26, no. 17, pp. 3048–3055, Sep. 2008.

[6] M. Yasin, H. Arof, and S. Harun, “Chapter 11: self-coherent reflective passive optical networks,” in *Advances in Optical Fiber Technology: Fundamental Optical Phenomena and Applications*. Rijeka, Croatia: InTech, Feb. 2015, pp. 365–386.

[7] Z. Vujičić *et al.*, “Self-homodyne detection-based fully coherent reflective PON using RSOA and simplified DSP,” *IEEE Photon. Technol. Lett.*, vol. 27, no. 21, pp. 2226–2229, Nov. 2015.

[8] S. Straullu, F. Forghieri, V. Ferrero, and R. Gaudino, “Optimization of self-coherent reflective PON to achieve a new record 42 dB ODN power budget after 100 km at 1.25 Gbps,” *Opt. Exp.,* vol. 20, no. 28, pp. 29590–29598, Dec. 2012.

[9] N. Cvijetic, D. Qian, J. Hu, and T. Wang, “Orthogonal frequency division multiple access PON (OFDMA-PON) for colorless upstream transmission beyond 10 Gb/s,” *J. Sel. Areas Commun.*, vol. 28, no. 6, pp. 781–790, Aug. 2010.

[10] Q. Feng *et al.*, “Impacts of backscattering noises on upstream signals in full-duplex bidirectional PONs,” *Opt. Exp.*, vol. 23, no. 12, pp. 15575–15586, Jun. 2015.

[11] M. Fleyer, J. P. Cahill, M. Horowitz, C. R. Menyuk, and O. Okusaga, “Comprehensive model for studying noise induced by self-homodyne detection of backward Rayleigh scattering in optical fibers,” *Opt. Exp.*, vol. 23, no. 20, pp. 25635–25652, Oct. 2015.

[12] W. Q. Jin and J. M. Tang, “Experimental investigations of wavelength spacing and colorless of RSOA-based ONUs in real-time optical OFDMA PONs,” *J. Lightw. Technol.*, vol. 30, no. 16, pp. 2603–2609, Aug. 2012.

[13] D. H. Kim, P. Y. Xing, Y. Y. Won, S. J. Park, and S. K. Han, “Bidirectional 1.25 Gb/s colorless RSOA based WDM-PON using suppressed optical carrier and polarization beam splitter,” in *Proc. Opt. Fiber Commun. Conf. Expo., Nat. Fiber Opt. Eng. Conf.*, 2008, Paper JThA97.

[14] S. M. Jung, S. M. Yang, K. H. Mun, and S. K. Han, “Optical beat interference reduction using out-of-band RF clipping tone signal in remotely fed OFDMA-PON link,” *Opt. Exp.*, vol. 22, no. 15, pp. 18246–18253, Jul. 2014.

[15] H. Kim, “Long-reach WDM-PON using directly modulated RSOAs and subcarrier multiplexing,” in *Proc. Opt. Fiber Commun. Conf. Expo., Nat. Fiber Opt. Eng. Conf.*, 2012, Paper OW1B.3.

[16] P. J. Urban, A. M. J. Koonen, G. D. Khoe, and H. Waardt, “Interferometric crosstalk reduction in an RSOA-based WDM passive optical network,” *J. Lightw. Technol.*, vol. 27, no. 22, pp. 4943–4953, Nov. 2009.

[17] E. K. MacHale *et al.*, “Signal-induced rayleigh noise reduction using gain saturation in an intergrated R-EAM-SOA,” in *Proc. Opt. Fiber Commun. Conf. Expo., Nat. Fiber Opt. Eng. Conf.*, 2009, Paper OThA6.

[18] C. H. Yeh and C. W. Chow, “Using single side-band modulation for colorless OFDM-WDM access network to alleviate rayleigh backscattering effects,” *Opt. Exp.*, vol. 24, no. 10, pp. 10898–10903, May 2016.

[19] J. M. Lee, Y. Y. Won, and S. K. Han, “Back-scattering noise reduction using RF tone in RSOA-based bidirectional optical access link,” *Microw. Opt. Technol. Lett.*, vol. 53, no. 2, pp. 331–334, Feb. 2011.

[20] J. Mora *et al.*, “Photonic microwave tunable single-bandpass filter based on a Mach-Zehnder interferometer,” *J. Lightw. Technol.*, vol. 24, no. 7, pp. 2500–2509, Jul. 2006.