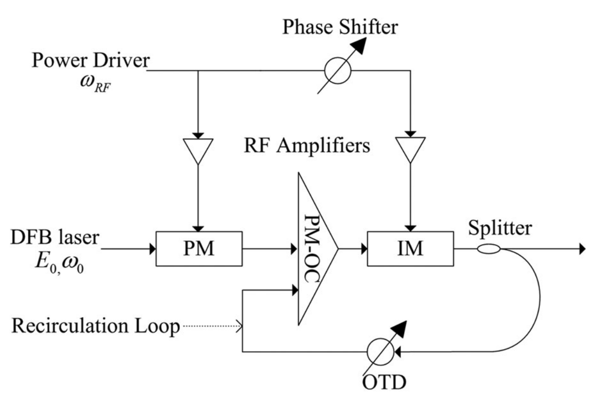
IEEE Photonics Journal
An IEEE Photonics Society Publication

Tunable Multiwavelength Optical Comb Enabled WDM-OFDM-PON With Source-Free ONUs

Volume 10, Number 3, June 2018

Xuwei Xue, ***Student Member, IEEE***
Wei Ji
Kangrui Huang
Xiao Li
Shicheng Zhang



DOI: 10.1109/JPHOT.2018.2827306

Tunable Multiwavelength Optical Comb Enabled WDM-OFDM-PON With Source-Free ONUs

Xuwei Xue, *Student Member, IEEE*, Wei Ji, Kangrui Huang, Xiao Li, and Shicheng Zhang

School of Information Science and Engineering, Shandong University, Jinan 250000, Shandong, China

DOI:10.1109/JPHOT.2018.2827306

Manuscript received February 28, 2018; revised March 27, 2018; accepted April 11, 2018. Date of publication April 12, 2018; date of current version May 8, 2018. This work was supported in part by the National Natural Science Foundation under Grants 61571273 and 61771292, in part by The National Key Research and Development Program of China under Grant 2017YFC0803403, in part by Natural Science Foundation of Shandong Province of China under Grant ZR2016FM29, and in part by the Fundamental Research Funds of Shandong University. Corresponding author: Wei Ji (email: jiwww@sdu.edu.cn).

Abstract: In this paper, we propose and experimentally demonstrate a multiuser wavelength-division-multiplexing passive optical network (WDM-PON) system combining with orthogonal frequency division multiple (OFDM) technique. A tunable multiwavelength optical comb (MOC) is designed to supply flat optical lines for assisting the configuration of the proposed multiple source-free optical network units enhanced WDM-OFDM-PON system. Schematized by cascading a phase modulator and an intensity modulator with a recirculation loop, the MOC can output 29 ideal channel optical comb lines with the flatness of 0.85 dB. For the MOC enabled WDM-OFDM-PON system, source-free and interference-free multiuser upstream transmission over a single fiber can be efficiently supported, while downstream transmission channels can convey the baseband data stream and radio frequency OFDM signals simultaneously so that the proposed system can be connected to wire-line users and wireless users simultaneously.

Index Terms: Passive optical network (PON), source-free ONUs, optical comb, wired and wireless hybrid system.

1. Introduction

With the ever-increasing services such as video-on-demand, internet protocol television (IPTV) and high-definition television (HDTV), cost-effectiveness has become a key factor for the further development of PON systems, especially for the next-generation PON system requiring more than 64 optical network units (ONUs) [1]. However, the high cost of provision of dedicated fibers and the requirement of a wavelength specific laser source at each ONU are the major limitations in the realization of high speed broadband access network infrastructure [2]. To solve these problems, many investigations have been done to reduce the cost of PON system, such as signal remodulation technique using electroabsorption modulator (EAM), reflective semiconductor optical amplifier (RSOA) [3]–[4] or injection-locked FabryProt laser diode (FP-LD) [5]–[6] and ONU-side optical source delivering technique. The above-mentioned techniques mainly aim to make each ONU free of optical source in the optical domain. Nevertheless, the deployment of the RSOA and FP-LD at

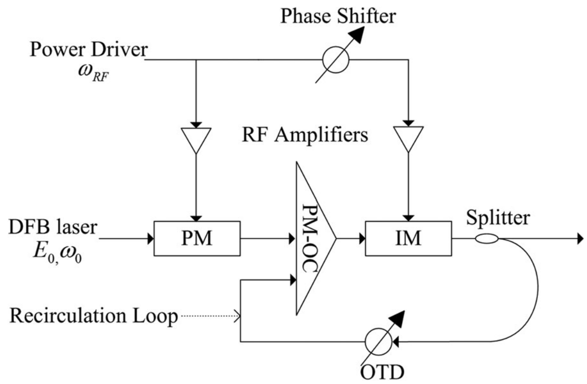


Fig. 1. Schematic diagram of multi-wavelength optical comb (MOC), PM-OC: polarization maintaining optical coupler, OTD: optical time delayer.

PON could increase the cost and introduce the complicated operations satisfying the high precision requirements of the optical components. In this paper, we design and implement a tunable multi-wavelength optical comb (MOC) enabled source-free ONUs for PON system, in which the MOC supplys flat, square-shaped multi-wavelength optical comb lines. Half part of MOC output optical lines are utilized to carry wired and wireless hybrid signals for the downstream transmission, and the remaining optical lines support interference-free multiuser upstream transmission. A detailed theoretical analysis is presented, showing that this proposed MOC architecture with a recirculation loop can significantly improve output performance, generating more flat comb lines compared with the traditional multiwavelength light sources. The scheme proposed in [7] could achieve 25 optical lines with a power variation 0.9 dB, but the joint operation of a polarization modulator (PolM), a polarizer and the synchronization of two RF signals introduce a sophisticated operation. As compared with the 11 comb-line generator demonstrated in [8], the MOC we implemented could generate 29 comb lines featuring flatness performance. A power controller is employed to ensure the flatness of the proposed comb generator in [9], and the power value should be tuned before generating specified number of combs, which could lead to the unstable performance. The proposed MOC provides sufficient WDM channels, which greatly reduce the number of independent lasers and simplify the controlling process [10]–[12].

For the realization of MOC-enabled PON system, we use WDM technique to separate ONUs into several virtual point-to-point connections over the same physical infrastructure, a feature that enables efficient use of fiber and offers lower latency than time division multiplexing (TDM) based approaches [13]. As a promising multi-user access technology, orthogonal frequency division multiplexing (OFDM) technique is also employed in the MOC-enabled PON system due to its high spectrum efficiency and excellent robustness to chromatic dispersion [14]. To further improve the transmission efficiency, the downstream wired and wireless hybrid signals employ different frequency and modulation formats, so that these colourless ONUs can be connected with both wired users and wireless users. This MOC-enabled PON scheme combining with WDM-OFDM techniques has several attractive features: (1) the MOC provides superb flatness comb lines with tunable frequency; (2) all the ONUs are source-free and each unit has dedicated wavelength for the interference-free upstream transmission; (3) the hybrid downstream carrying both baseband and RF-OFDM signals ensure multi-scene applicability.

2. Principle of Multi-Wavelength Optical Comb

The schematic diagram of the proposed MOC is shown in Fig. 1. We employ the concatenation of a phase modulator (PM) and an intensity modulator (IM) with a recirculation loop to yield sufficient stable subcarriers. The PM is used to generate several comb lines over a wide frequency range which improves the scalability of the generated optical comb, while the IM with the recirculation loop is used to flatten the spectrum of the generated comb by properly adjusting the proportion of recirculation loop which means the power percentage of the IM output split to the recirculation loop link.

The continuous wave ($E_0 e^{jw_0 t}$) with frequency w_0 and amplitude E_0 generated from one narrow line-width laser is modulated by PM and IM sequently. Each modulator is driven by the RF clock signal ($V_{rfk} cos(w_{rf} t)$) with a tunable frequency w_{rf} and amplitude V_{rfk}. A splitter is responsible for supplying recirculation comb lines which are connected with the output of the first modulator via a polarization-maintaining optical coupler (PM-OC). An optical time delayer (OTD) is utilized to change the length of recirculation loop to ensure the input of PM-OC coupling is at the most appropriate point. The output optical field $E_{out}(t)$ of the k^{th} modulator can be represented as a series of harmonic frequency components $w_0 + i w_{rf}$, and i represents the harmonic number, $i \in [0, \pm 1, \pm 2, \ldots]$. The total field $E_{out}(t)$ of the k^{th} modulator is given by

$$E_{out}(t) = E_0 \cdot \sum_i \varepsilon_i \tag{1}$$

$$\varepsilon_i = A_{i,k} \cdot cos[2\pi(w_0 + i w_{rf})t + \theta_{i,k}]$$

$$A_{i,k} = \frac{1}{2} \cdot cos[(-1)^i \cdot \varphi_{DC}] \cdot J_i(C)$$

$$\theta_{i,k} = [1 + i + (-1)^i]\frac{\pi}{2} + \varphi_k$$

$C = \pi \frac{V_{rfk}}{2V_\pi}$ is the modulation depth, and V_π is the half-wave voltage of the modulator and $\varphi_{DC} = \pi \frac{V_{DCk}}{2V_\pi}$ is the phase shift caused by the V_{DCk}. V_{DCk} and φ_k represent the direct current bias voltage and the phase of the drive signal of the k^{th} modulator respectively. $J_i(C)$ is the ith order Bessel function of the first kind.

In order to obtain more stable subcarriers, we cascade an intensity modulator. By considering each component generated from the first phase modulator as continuous wave input to the second modulator, and summing all of the harmonic frequency components $w_0 + i w_{rf}$ from the first modulator, we obtain the total output field ($\hat{E}_{out}(t)$) of the second intensity modulator.

$$\hat{E}_{out}(t) = E_0 \cdot \sum_i \varepsilon_j \tag{2}$$

$$\varepsilon_j = \frac{1}{2} \sum_j A_{i,1} \{[(-1)^{2i-j} \cdot A_{i-j,2} + (-1)^j A_{j-i,2}]$$

$$\cdot\, cos[2\pi(w_0 + j w_{rf})t + i \cdot \frac{\pi}{2} + \varphi_1 + \varphi_2]\}$$

From (1) and (2), we can see that the RF amplitudes (V_{rf1}, V_{rf2}), direct current bias voltage (V_{DC1}, V_{DC2}) and phase of RF clock signals (φ_1, φ_2) can be used to control the relative amplitudes of each comb line, giving excellent control of the profile of the generated comb signals. The tunable frequency w_{rf} of the RF clock signal determines the frequency interval of comb lines. All the parameters of should be carefully adjusted to generate more harmonic frequency components with flat amplitude.

In order to generate multiple subcarriers with high optical signal noise ratio (OSNR) and ideal flatness, the amplitude of the RF clock signal after one electrical amplifier should be a few times greater than the half-wave voltage of modulator. Fig. 2 shows a more detailed analysis of the impact of the RF driving voltage on the power deviation of the output optical sidebands, in which the Z-axis represents the flatness of the output comb lines. Under these restrictive conditions, RF driving voltages are set independently for PM and IM. It is clear that the V_{rfk} about 2.5 to 3.5 V_π are necessary to achieve ideal flatness, and the flatness of 1.92 dB can be obtained. We choose $V_{rfk} = 3.0\ V_\pi$ as the experimental operating position, as described below, with a flatness of less than 2 dB. In our experimental setup, a distributed-feedback (DFB) laser at 1552.52 nm works as the

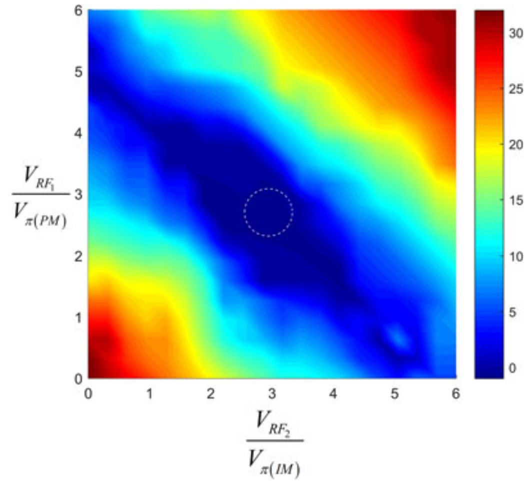


Fig. 2. Optimised comb optical flatness (minimum 1.92 dB marked by the circle) versus driving voltage applied to each modulator

optical source of the MOC and a 50 GHz sinusoidal RF source drives the cascaded PM and IM.The typical bandwidth response is 40 GHz for IM and PM, and the typical extinction ratio is 32 dB for IM and 25 dB for PM.

Different from the traditional schemes of multi-wavelength light source, a recirculation loop between two modulators is deployed in our experimental scheme to yield flat comb lines. Fig. 3 gives three optical spectra of optical frequency combs generated by the MOC when the recirculation proportion (RP) is 0%, 17%, and 45% respectively. In our experimental test, the OSNR of output combs for 0%, 17% and 45% recirculation proportion is 19.8 dB, 25.4 dB and 13.6 dB respectively. It is clear that the number of comb lines is continuously increased with the enlarged proportion of the recirculation loop. As the RP enlarged to 17%, the number of comb lines reach to 29. Furthermore, with the increasing of comb lines, the comb performance such as the power flatness is drastically deteriorated because of the introduced noises from the recirculation loop link. Based on the principle as described in (1)–(2), the frequency of the RF clock signal determines the frequency interval of comb lines, so by changing the frequency w_{rf}, the frequency interval of comb lines can be accordingly tuned with real needs. As shown in Fig. 4(a), RF signal with 30 GHz frequency is used to drive the IM and PM, and 0.84 THz channel spacing can be observed with the 30 GHz frequency interval of comb lines. When the frequency of RF source equals to 50 GHz, the total channel spacing is 1.4 THz (28*50 GHz) as illustrated in Fig. 4(b).

The number of comb lines and the optical power flatness are measured with the changes of recirculation proportion, as illustrated in Fig. 5, when the DC biases and relative optical phases are in the optimal states and $V_{rfk} = 3.0\ V_{\pi}$. The blue circles show the relationship between the measured number of comb lines and the changes of the recirculation proportion. As we can observe, the increase of the comb line number is nearly proportional to the increase of the recirculation proportion. Meanwhile, for the measured optical power flatness, as shown in the red triangles, there is drastic fluctuation with the changes of the recirculation proportion. Based on the principle as described in (1)–(2), there are i optical comb lines inputted to the IM and each of them can be motivated to another j spectral lines by IM together with the recirculation loop. The feedback $i * j$ comb lines from recirculation loop could compensate the input edge lines of IM to power align with the central lines, which could flat the spectrum of the generated combs with the aid of small recirculation proportion. When the recirculation proportion is 17% of the IM output power, the generated 29 comb lines can obtain negligible power variation 0.85 dB. However, with the increasing of recirculation proportion, the noises introduced by the feedback combs could disrupt the spectrum flatness, because the amplitude of feedback $i * j$ comb lines could be larger than those of the original i optical combs. The high power of the feedback lines also makes it hard to ensure

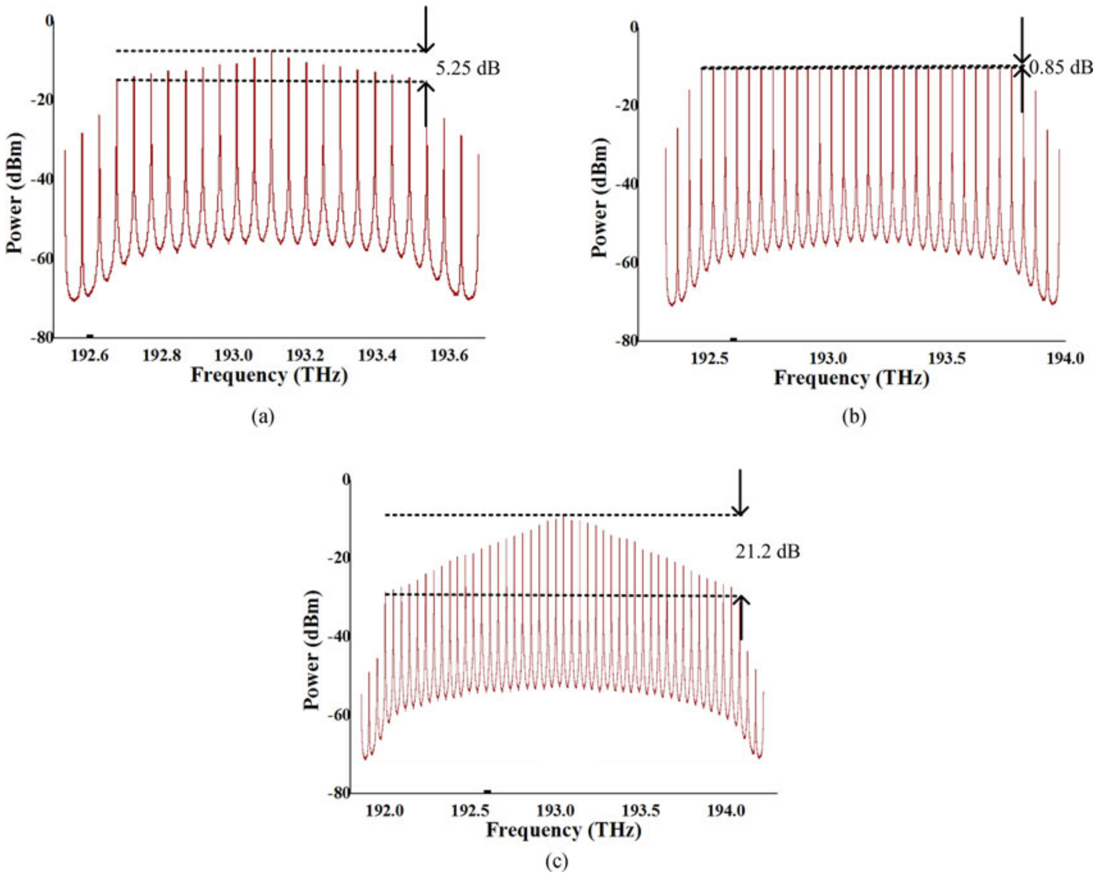


Fig. 3. Optical spectrum versus different proportion of recirculation loop. (a) 0% RP with 19 combs, (b) 17% RP with 29 combs, (c) 45% RP with 45 combs.

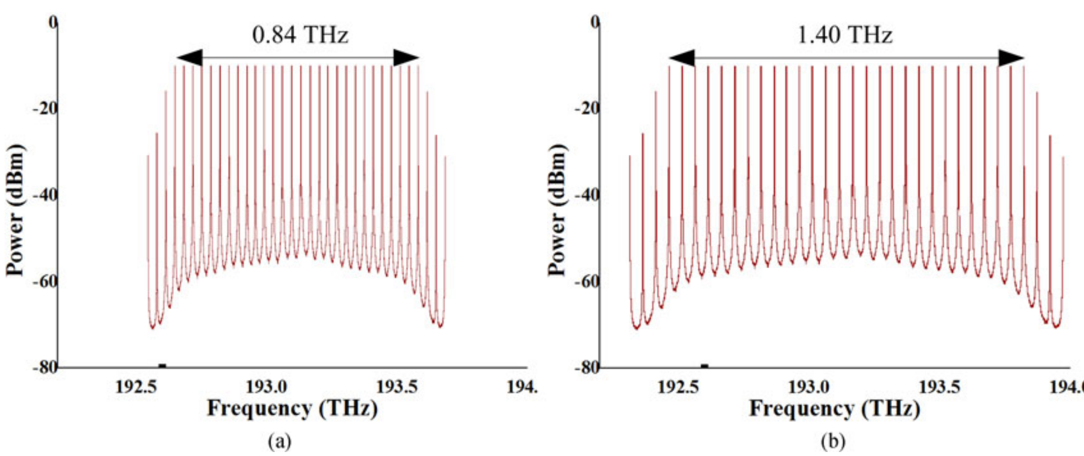


Fig. 4. Optical spectrum versus different frequency of RF source. (a) 30 GHz and (b) 50 GHz.

the input of PM-OC coupling at the most appropriate point. When the recirculation proportion is 17% of the IM output power, the MOC we implemented has 29 comb lines with intensity deviation of less than 1 dB. The MOC with a great number of comb lines is more suitable for the next PON system requiring more than 64 ONUs. Hence, we can employ this MOC to generate flat optical lines with tuneable frequencies for the use of PON system with source-free OUNs.

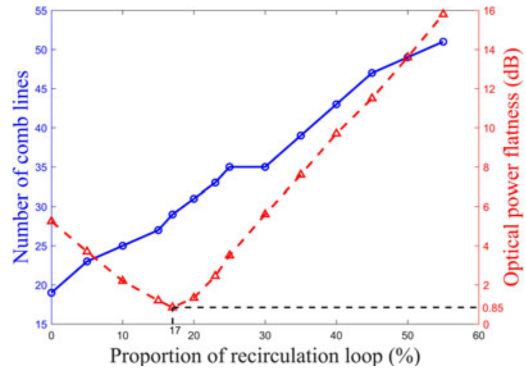


Fig. 5. Number of comb lines and optical power flatness versus different proportions of recirculation loop.

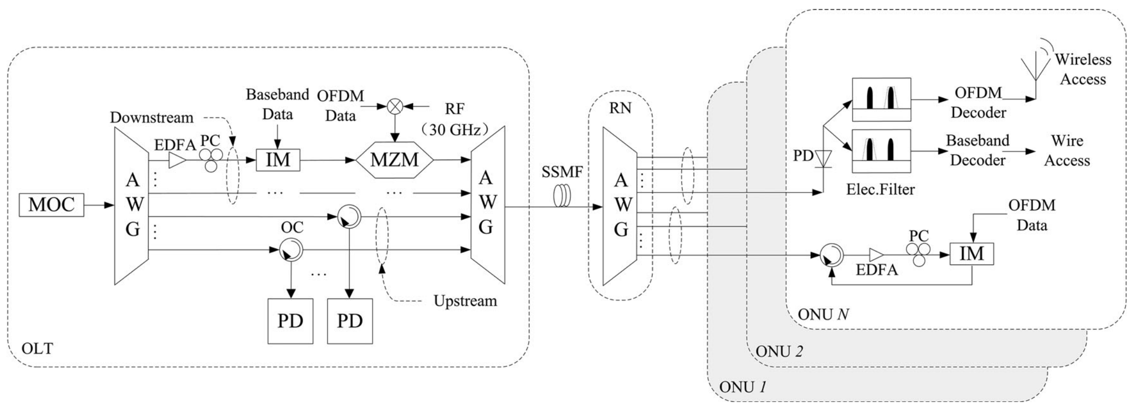


Fig. 6. Setup of the proposed WDM-OFDM-PON, RN: route node, IM: intensity modulator, MZM: Mach-Zehnder modulator, OC: optical circulator, PC: polarization controller.

3. Operation Principle of Proposed WDM-OFDM-PON

As can be seen from (1)–(2) and the definition of i and j, the MOC can generate 2N + 1 comb lines, with a tunable frequency grid of w_{rf}. In consequence, for a MOC enabled WDM-OFDM-PON with multiple source-free ONUs, such as 14 ONUs, we only need to control DC biases, relative optical phases, driving voltage of RF clock signals and proportion of recirculation loop to generate 29 comb lines with superb flatness to carry downstream and upstream signals. 14 of these comb lines can be employed to support downstream transmission carrying baseband data stream and RF-OFDM signals simultaneously, and these remaining 14 comb lines can be utilized to support interference-free upstream transmission enabling source-free ONUs. The experimental setup of the proposed MOC enabled WDM-OFDM-PON with source-free ONUs is shown in Fig. 6.

In the optical line terminal (OLT), the MOC generates 29 comb lines with flatness of less than 1 dB. 14 of them are modulated by an intensity modulator with baseband data after passing a 6 dB erbium doped fiber amplifier (EDFA) and a polarization controller (PC), and then are up-converted by Mach-Zehnder modulator with RF-OFDM data. The remaining 14 comb lines without carrying signals are used to support interference-free upstream transmissions. The 10 Gb/s of 4 quadrature amplitude modulation (QAM)-OFDM signal is generated off-line and is uploaded into a Tektronix arbitrary waveform generator (AWG7102) at 10 Gsample/s with 8-bit resolution. The OFDM data has 128 size of inverse discrete Fourier transform (IDFT), 256 total subcarriers and 100 symbols cyclic prefix (CP). In addition, a training sequence is inserted in front of all the symbols for window synchronization. These 28 comb lines are combined by an arrayed waveguide grating (AWG) and propagate over 20 km standard single mode fiber (SSMF) with 17 ps/(nm.km) chromatic dispersion, one downstream comb line and one upstream comb line are delivered into the corresponding ONU

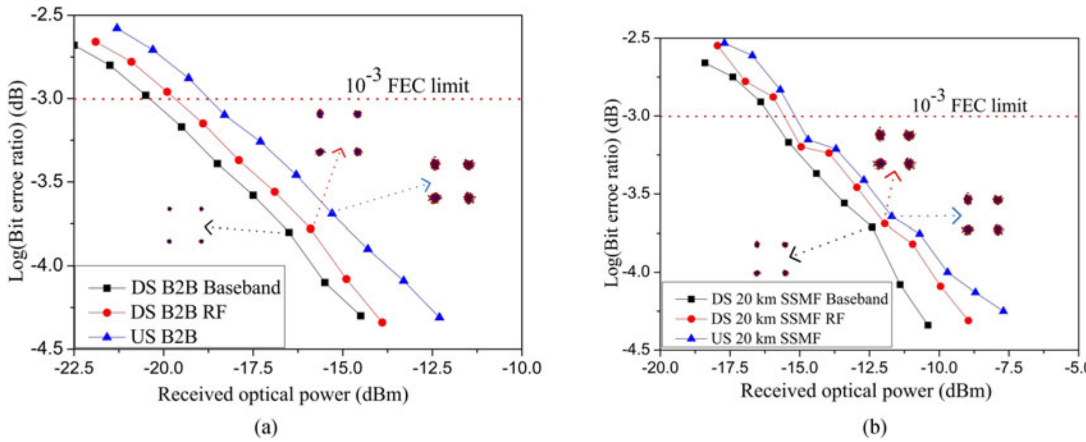


Fig. 7. Measured BER and normalized constellations versus received optical power, US: upstream, DS: downstream, FEC: forward error correction.

simultaneously. The downstream comb line is detected by a photodetector. After the a filter, the RF-OFDM data is delivered to wireless users and baseband data stream is dispatched to users by wire-line directly. After passing a 11 dB EDFA and polarization controller, the upstream comb line is fed into an IM for 10 Gb/s OFDM signal modulation and redirected to the OLT through a circulator. Thus there are no lasers and coloured components at the ONU side for upstream transmission.

Fig. 7 shows the measured bit-error-rate (BER) curves and the normalized constellations versus received optical power after back to back (B2B) and 20 Km transmission of the proposed WDM-OFDM-PON system. The power penalty for downstream and upstream transmissions is about 1 dB for back to back transmission and 0.8 dB for 20 km SSMF transmission at a BER of 10^{-3}. After 20 km SSMF, the received 4QAM constellations have been effectively recovered for both upstream and downstream receptions, which demonstrates that the proposed MOC could supply sufficient and stable combs for the WDM-OFDM-PON.

4. Conclusion

We have proposed and demonstrated a cost-effective WDM-OFDM-PON, in which all the ONUs are source-free for the upstream channels, enabled by a tunable multi-wavelength optical comb. The desired number of comb lines with ideal flatness can be achieved thanks to the unit of the recirculation loop. For the proposed WDM-OFDM-PON system, the frequency interval of comb lines can be accordingly tuned with real needs. The downstream channels carry wired and wireless hybrid signals to different users and no light sources and colored components are needed in the ONUs, which effectively reduce the cost and simplify the controlling process. Consequently, the WDM-OFDM-PON architecture we verified is scalable and cost-effective, and it is promising for application in the next generation broadband optical access networks.

Acknowledgements

The authors would like to thank Lei Zhu (Huazhong University of Science and Technology) for the discussions.

References

[1] N. Cvijetic *et al.*, “Orthogonal frequency division multiple access PON (OFDMA-PON) for colorless upstream transmission beyond 10 Gb/s,” *IEEE J. Sel. Areas Commun.*, vol. 28, no. 6, pp. 781–790, Aug. 2010.

[2] S. Chatzi and T. Ioannis, “Techno-economic study of high-splitting ratio PONs and comparison with conventional FTTH-PONs/FTTH-P2P/FTTB and FTTC deployments,” in *Proc. Opt. Fiber Commun. Conf.*, 2011, pp. 1–3.

[3] P. K. Choudhury and Z. K. Tanvir, “Symmetric 10Gb/s wavelength reused bidirectional RSOA based WDM-PON with DPSK modulated downstream and OFDM modulated upstream signals,” *Opt. Commun.*, vol. 372, no. 4, pp. 180–184, 2016.
[4] D. Kim *et al.*, “Carrier-phase-estimation algorithm featuring fast trackability for high-speed coherent WDM PON based on RSOA,” *Opt. Exp.*, vol. 25, no. 13, pp. 14282–14289, 2017.
[5] Y. Luo *et al.*, “10-Gb/s all-optical VPN in WDM-PON using injection-locked FabryPérot laser diodes,” *IEEE Photon. Technol. Lett.*, vol. 26, no. 22, pp. 2299–2302, Nov. 2014.
[6] W. Cui, S. Tong, and Y. Jianping, “Wavelength reuse in a UWB over WDM-PON based on injection locking of a FabryPérot laser diode and polarization multiplexing,” *J. Lightw. Technol.*, vol. 32, no. 2, pp. 220–227, Jan. 2014.
[7] C. He *et al.*, “Ultraflat optical frequency comb generated based on cascaded polarization modulators,” *Opt. Lett.*, vol. 37, no. 18, pp. 3834–3836, 2012.
[8] N. Yokota *et al.*, “Harmonic superposition for tailored optical frequency comb generation by a Mach–Zehnder modulator,” *Opt. Lett.*, vol. 41, no. 5, pp. 1026–1029, 2016.
[9] C. Chen, C. Zhang, and D. Liu, “Tunable optical frequency comb enabled scalable and cost-effective multiuser orthogonal frequency-division multiple access passive optical network with source-free optical network units,” *Opt. Lett.*, vol. 37, no. 19, pp. 3954–3956, 2012.
[10] S. Fukushima, C. F. C. Silva, Y. Muramoto, and A. J. Seeds, “Optoelectronic millimeter-wave synthesis using an optical frequency comb generator, optically injection locked lasers, and a unitraveling-carrier photodiode,” *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3043–3051, Dec. 2003.
[11] P. Shen, N. J. Gomes, P. A. Davies, P. G. Huggard, and B. N. Ellison, “Analysis and demonstration of a fast tunable fiber-ring-based optical frequency comb generator,” *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3257–3264, Nov. 2007.
[12] K. P. Ho and J. M. Kahn, “Optical frequency comb generator using phase modulation in amplified circulating loop,” *IEEE Photon. Technol. Lett.*, vol. 5, no. 6, pp. 721–725, Jun. 1993.
[13] C. Chen *et al.*, “Scalable and reconfigurable generation of flat optical comb for WDM-based next-generation broadband optical access networks,” *Opt. Commun.*, vol. 321, pp. 16–22, 2014.
[14] X. Xue, W. Ji, and Z. Kang, “High-efficiency optical coupling single-sideband modulation for OFDM-RoF-PON systems,” *Opt. Commun.*, vol. 356, pp. 500–509, Dec. 2015.