Bidirectional Radio Frequency Up-Converted Orthogonal Frequency-Division Multiple Access Passive Optical Network With Novel Source-Free Optical Network Units Using Four-Wave Mixing in Semiconductor Optical Amplifier

Chen Chen, Chongfu Zhang, Yuan Feng, and Kun Qiu

***Abstract*— We propose and demonstrate a bidirectional radio-frequency (RF) up-converted orthogonal frequency-division multiple access passive optical network (OFDMA-PON) system. Novel source-free optical network units (ONUs) are configured in the proposed OFDMA-PON system, which can support simultaneous and interference-free upstream transmission from multiple ONUs over a single wavelength in a single-fiber topology. The four-wave mixing effect in a semiconductor optical amplifier is utilized in the optical line terminal to enable its configuration. Experimental results successfully verify the feasibility of our proposed system.**

***Index Terms*— Four-wave mixing (FWM), orthogonal frequency-division multiple access (OFDMA), passive optical network (PON), source-free.**

I. Introduction

PASSIVE optical networks (PONs) have being attracting tremendous attention for being viewed as an economic and 'future-proof' strategy to meet the rising demand of bandwidth-hungry multimedia applications in the multiuser access networks. PON systems based on the employment of orthogonal frequency-division multiple access (OFDMA) is a promising multiuser access technology thanks to its great flexibility of dynamic bandwidth allocation and its easy upgrade of end customers [1], [2]. A mass of investigations focused on the optically source-free feature of ONUs in PON systems have already been reported recently, for example, the lightwave centralization technique or the approach of signal re-modulation in electro-absorption modulator (EAM) or reflective semiconductor optical amplifier (RSOA) [3]–[5]. In this letter, these techniques are primarily designed to make each ONU free of optical source in the optical domain.

In a typical optical OFDMA-based PON system, baseband OFDMA signal is usually firstly up-converted to the radio frequency (RF) domain before the optical modulation and the fiber link transmission. RF up-conversion could create a frequency guardband between optical carrier and OFDMA signal band and it can effectively prevent the transmitted OFDMA signal from severe deterioration induced by non-coherent mixing products [6]. In consequence, every ONU requires at least one electric domain RF source to down-convert the downstream (DS) received RF OFDMA signal as well as up-convert the upstream (US) transmitted baseband OFDMA signal. An interesting architecture of source-free OFDMA-PON system is proposed in reference [7], in which the US OFDMA signals from multiple ONUs are transmitted over a single wavelength enabled by carrier suppression. In order to eliminate the interference of the US signals coming from different ONUs, each US signal is up-converted to a unique frequency and then all of these US signals are separately distributed on the US re-used wavelength to avoid any signal overlapping. Therefore, each ONU must need one RF source with a unique frequency and thus all the RF sources required by multiple ONUs would locate in a much higher frequency range, especially when the number of connected ONUs increases or the US signal bandwidth of each ONU channel aggrandizes. In fact, the frequency level of now available commercial electrical clock source is relatively low and meanwhile cost-efficient high-frequency electrical clock source is practically unavailable. The possibility of cutting ONU-side RF clock source has been successfully verified in our previous work [8] by employing polarization multiplexing in the OLT, thus the ONU is source-free not only optically but also electrically. Nevertheless, this approach can only generate RF source with a fixed frequency and it is evidently inapplicable to support simultaneous and interference-free US transmission from multiple ONUs over a single wavelength in a single-fiber topology OFDMA-PON system.

We for the first time propose such a bidirectional RF up-converted OFDMA-PON system, wherein all of the

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The authors are with the Key Laboratory of Optical Fiber Sensing and Communication Networks (Ministry of Education) and School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China (e-mail: cfzhang@uestc.edu.cn).

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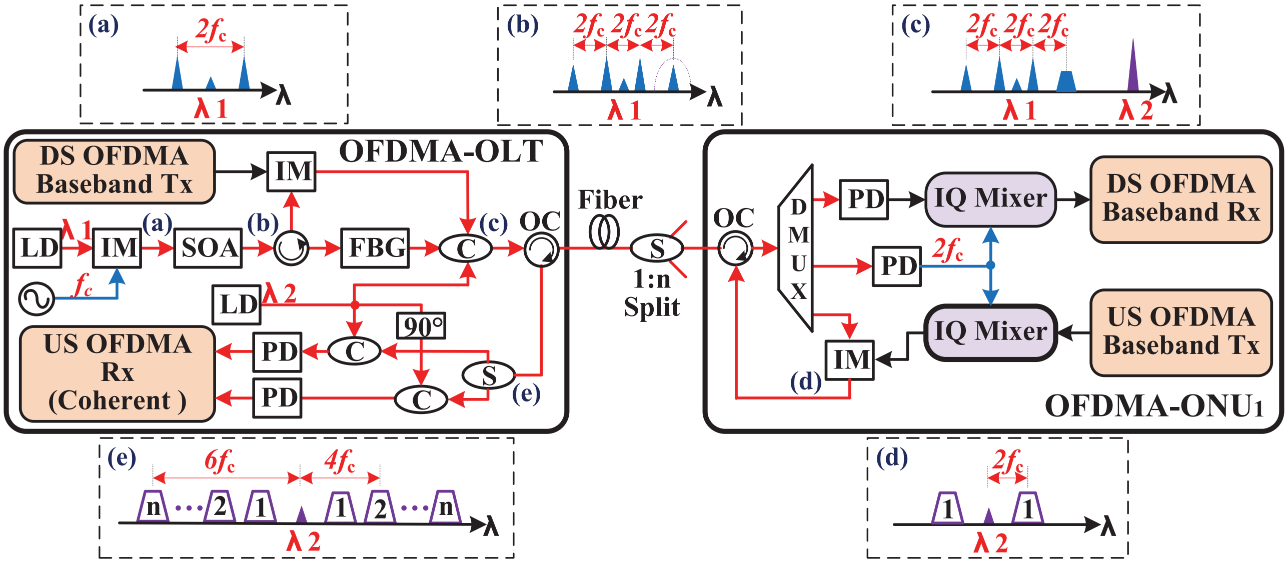

Fig. 1. Principle of the proposed OFDMA-PON system and the corresponding spectrum diagrams for different stages.

ONUs are source-free both optically and electrically. Furthermore, this system can efficiently support simultaneous and interference-free US transmission from multiple ONUs over a single wavelength in the single-fiber topology. In the OLT, a semiconductor optical amplifier (SOA) is utilized to perform four-wave mixing (FWM) effect and help configure this system due to its easy integration and polarization insensitivity [9], [10].

II. Principle

The fundamental principle of the proposed novel source-free OFDMA-PON system is shown in Fig. 1. Two continuous-wave (CW) laser sources are used in the OLT: $\lambda 1$ is used for DS optical OFDMA transmission while $\lambda 2$ is transmitted to each ONU directly and re-used as a distributed carrier for US transmission. A sinusoidal RF source fc is used to drive an intensity modulator (IM) operating at $\lambda 1$ to perform optical carrier suppression (OCS) modulation. The output signal of IM shown in Fig. 1(a) is taken as the input of a SOA to perform FWM effect and generate two converted sidebands, as illustrated in Fig. 1(b). The right sideband is reflected by a narrowband fiber Bragg grating (FBG) filter and a circulator.

Then DS baseband OFDMA signal is modulated onto this sideband. After that, it is coupled with the signal passing through FBG and CW laser $\lambda 2$ for DS transmission, as given in Fig. 1(c). After transmitted along the fiber, DS signal is then split into multiple streams and each stream is received by an independent ONU. In the ONU, different frequencies of DS signal are separated by a de-multiplexer (DMUX). For ONU_1, a $2fc$ RF source is generated by the optical heterodyning of two selected optical pure bands with the frequency interval of $2fc$. The generated $2fc$ RF source is then used to down-convert the obtained DS $2fc$ OFDMA signal in the IQ mixer and up-convert the US baseband OFDMA signal in another IQ mixer. US OCS modulation is taken in the IM operating at $\lambda 2$ and the US OCS signal from ONU_1 is shown in Fig. 1(d). In order to avoid any signal overlapping between DS signal and US signal, the frequency interval between $\lambda 1$ and $\lambda 2$ should be sufficient enough. For the US transmission from multiple ONUs, RF clock source with a unique frequency is generated by the heterodyning in each ONU. US signals from multiple ONUs are respectively up-converted by $2fc$, $4fc$ and $6fc$ RF sources and separately distributed on the US re-used wavelength $\lambda 2$, as seen in Fig. 1(e). So our proposed OFDMA-PON system can support simultaneous and interference-free US transmission from multiple ONUs over a single wavelength in the single-fiber topology, meanwhile it can also feature the novel source-free virtue of its configuration at the same time.

III. Experiment and Discussion

Figure 2 shows the detailed experimental setup of our proposed novel source-free OFDMA-PON system. In order to better verify its feasibility as a bidirectional multiuser access system, single-fiber topology is adopted. Meantime, a variable optical attenuator (VOA) with 12 dB attenuation is used following the 20 km standard single mode fiber (SSMF) to emulate a 1:16 optical splitter. In the OLT, a distributed feedback (DFB) laser at 1549.82 nm with 10 dBm launch power is employed as DS CW source. A polarization controller (PC) is followed to control the laser output power and adjust polarization state. An IM driven by a 10 GHz sinusoidal source is biased at a minimum transmission point to perform OCS modulation. An erbium-doped fiber amplifier (EDFA) and an optical band pass filter (BPF) are used to increase the OCS signal power to 9.96 dBm and remove other high-order sidebands. Then the OCS signal inputs the SOA (CIP SOA-NL-OEC-1550), which is biased at 290 mA to perform the FWM effect and generate two converted sidebands. An FBG filter with 1-GHz passband and an optical circulator (OC) are utilized to reflect the right converted sideband, which is modulated with 10 Gb/s baseband 16QAM-OFDMA signal after a PC. The baseband 16QAM-OFDMA signal is generated

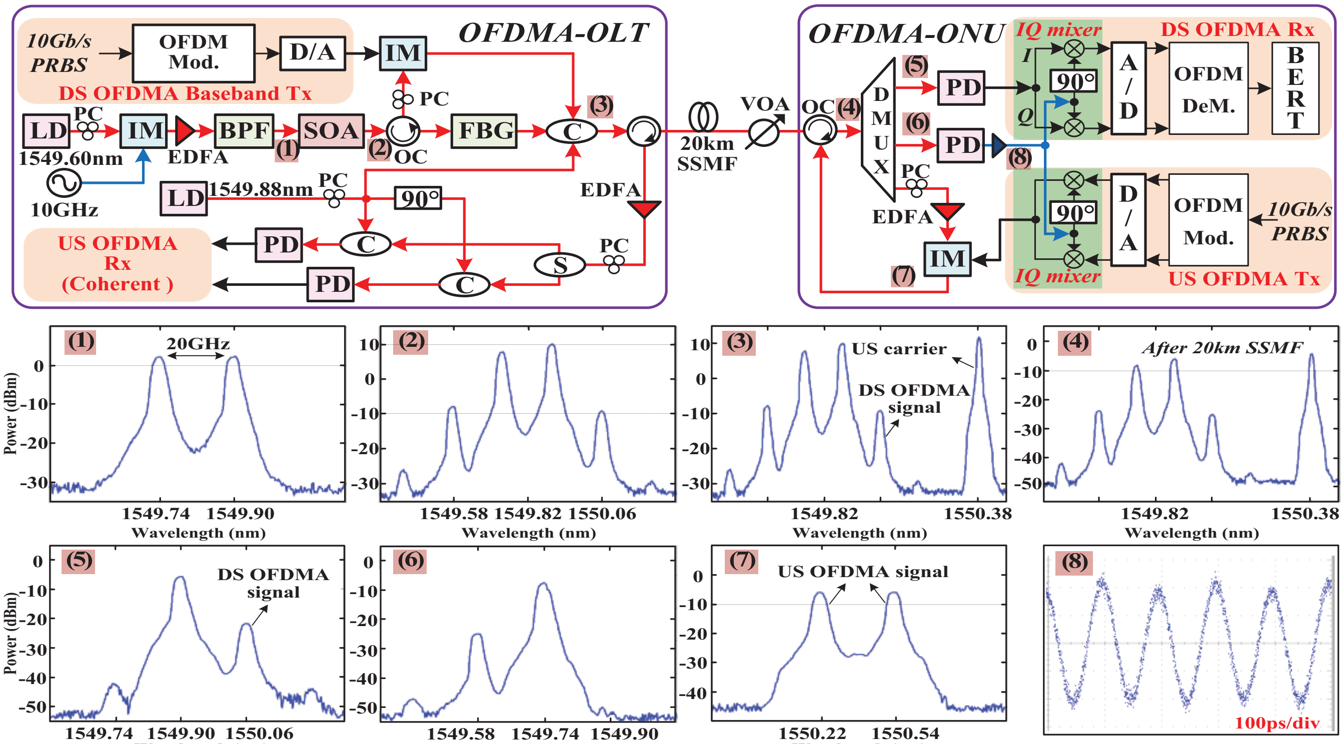

Fig. 2. Experimental setup of the proposed OFDMA-PON system and the corresponding spectra and waveform.

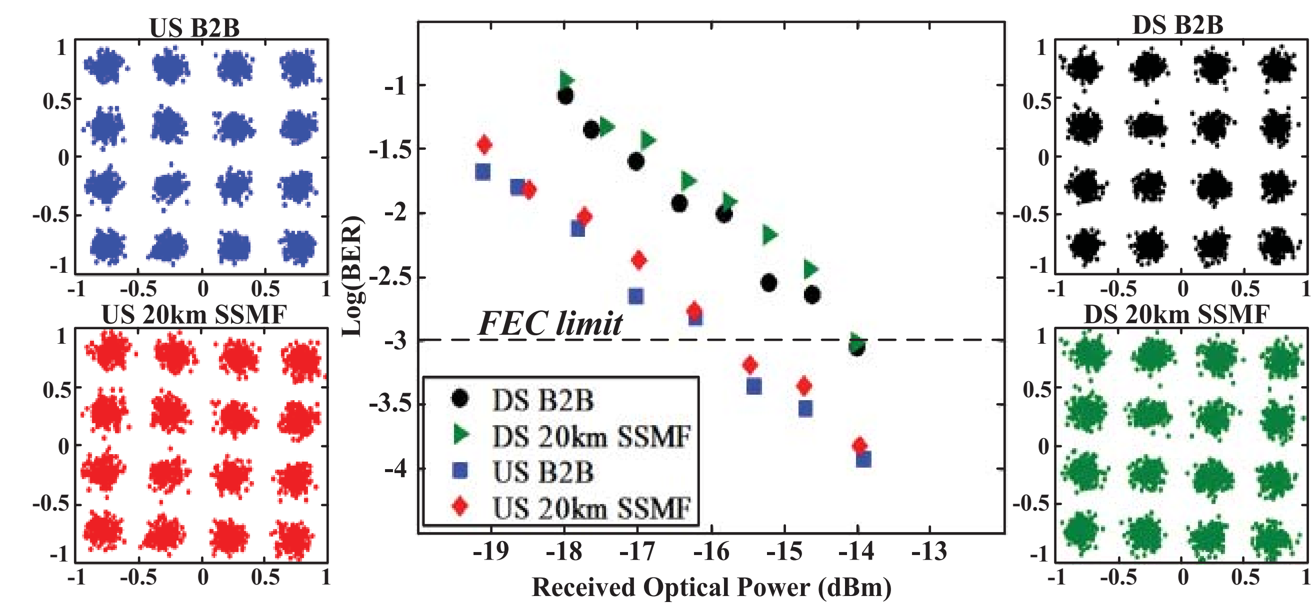

Fig. 3. Measured BER curves and normalized constellations for both DS and US transmissions after B2B and 20-km SSMF of the proposed system.

off-line with FFT size of 128 and 1/32 CP and it is uploaded into a Tektronix arbitrary waveform generator (AWG7102) at 10 Gsample/s with 8-bit resolution. A coupler is used to combine the reflected sideband and FBG transmitting bands as well as another 10 dBm DFB laser at 1550.38 nm together to form the downlink signal. The downlink signal with the launch power of 14.32 dBm is transmitted over 20 km SSMF and a 12 dB VOA. In the ONU, a spectral DMUX with 20 GHz bandwidth and 5 dB loss in each port is used to separate the downlink signal as three parts: (i) two sidebands in the middle, (ii) two pure sidebands in the left, and (iii) the right sideband. Two 20 GHz linear PIN photodiodes (PDs) are used to receive part (i) and (ii), respectively. DS 20 GHz OFDMA signal and a 20 GHz pure RF clock source are generated, resulting from the optical heterodyne in two PDs. Consequently, the achieved 20 GHz RF clock source is utilized to help down-convert DS 20 GHz OFDMA signal in an analog IQ-mixer and then the DS baseband OFDMA signal is obtained and analyzed off-line to get the DS bit-error-rate (BER) performance. While the achieved 20 GHz RF clock source is also used to up-convert the US 10 Gb/s baseband 16QAM-OFDMA signal in another analog IQ-mixer. Part (iii) is re-used as the US optical carrier after passing a PC and an EDFA. US 20 GHz OFDMA signal is modulated onto the US carrier in an IM with optical carrier suppression. Because each ONU can obtain a RF clock source with unique frequency, US signals coming from multiple ONUs can be separately distributed over the single wavelength US carrier without any signal overlapping. The uplink signal of about 8.29 dBm is launched into the same SSMF after an OC. Then it is coherently detected the OLT side in order to get a better US BER performance. Inserts (1)~(7) in Fig. 2 show the corresponding spectra of our experiment, which are captured by Tektronix optical spectrum analyzer (OSA-AQ6317B) with the resolution bandwidth of 0.5 nm. Insert (8) in Fig. 2 gives the waveform of ONU achieved 20 GHz pure RF clock source which is sampled by Tektronix real-time oscilloscope (DSA-72004C) at 50 Gsample/s. Although certain deterioration occurs, the generated RF clock source is pure and effective enough to assist both DS and US signals to fulfill the RF conversions.

Figure 3 shows the measured BER performance for both DS and US after back-to-back (B2B) and 20 km SSMF transmission, respectively. The forward error correction (FEC) limit of BER $= 10^{-3}$ is also plotted in Fig. 3 for reference. In the case of DS transmission, a received optical power (ROP) of about -14 dBm is required to reach the FEC limit, while the ROP required to reach the FEC limit is about -16 dBm in the case of US transmission. Furthermore, fiber dispersion induced power penalty is almost negligible for both DS and US transmission cases. Four inserts in Fig. 3 express the normalized constellations for both DS and US signals after B2B and 20 km SSMF transmission. It is clear that the 16-QAM constellations are effectively recovered both for the DS direct detection reception and the US coherent detection reception.

IV. Conclusion

We have proposed and demonstrated a bidirectional RF up-converted OFDMA-PON system. In our experiment, a single-fiber topology is adopted and the US optical carrier used in each ONU is remotely delivered via DS transmission from the OLT side. By utilizing the FWM effect in a SOA in the OLT side and optical heterodyning in the ONU side, novel source-free ONUs are successfully configured not only in the optical domain but also in the electric RF domain. Moreover, RF clock sources with multiple frequencies can be generated by optical heterodyning of two optical pure carriers with selected frequency intervals. Consequently simultaneous and interference-free US transmission from multiple ONUs over a single wavelength in a single-fiber topology can be efficiently supported in our proposed novel source-free OFDMA-PON system.

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