# An Ultra-dense Optical Comb Based DWDM-OFDM-PON System

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**Abstract**— We proposed and demonstrated an ultra-dense optical comb based DWDM-OFDM-PON scheme. At the optical line terminal (OLT), a cost-effective optical frequency comb generator (OFCG) is proposed and achieved as the multi-wavelength optical source. The OFCG is capable to provide multiple channels with reconfigurable wavelength spacing for ultra-dense WDM-PON based access network. In our scheme, OFDM signal with multi-level modulation will be encoded into the OFCG lines for the downstream transmission to enhance the spectral efficiency while the OFDM signal will be remodulated by OOK data for the upstream transmission due to its ease of implementation in optical network unit (ONU) side. In experiments, we demonstrated that 10 optical lines with 25 GHz channel spacing are generated and they were modulated by 2.5-GB/s QPSK-OFDM for the downlink signal transmission. We also demonstrated that the multiple wavelengths from the OFCG.

The demand bandwidth for end-to-end connectivity of broadband access services is expected to grow tremendous in the coming decades. Dense wavelength multiplexing-passive optical network (DWDM-PON) has been widely investigated for high data rate services [1–3]. In these paper, individual single wavelength laser was employed as continuous wave source providing carrier. The laser array in actual DWDM-PON is costly and unstable in maintaining coherence among multiple optical carriers. Optical frequency comb (OFC) [4–6] provides a alternative for the DWDM system lightwave source. Compared to the individual laser array, OFC generator based DWDM system simplifies the complexity of the system, lower the operation cost and promote the stability [7, 8]. OFC generated by cascading modulators is suitable for communication systems. Although in principle we can anticipate that more modulators can be used together to bring more comb lines, the complexity of the system, high operation cost and large power consumption will hinder the real applications of OFC in communication systems. On the other hand, orthogonal frequency-division multiplexing (OFDM) is considered as a strong candidate for future access network due to its contribution in high spectrum efficiency and resistance to dispersion effects and crosstalk, including inter-channel interference (ICI) and inter-symbol interference (ISI). It is also well known that of the OFDM technology is being widely applied in the fourth generation (4G) and the upcoming fifth generation (5G) mobile communication system thus it will be beneficial to investigate PON system employing OFDM infrastructure for the future seamless integration of wire-and-wireless communication system.

In this paper, we proposed an ultra-dense OFC based DWDM-OFDM-PON architecture, as illustrated in Figure 1. At the optical line terminal (OLT), an optical frequency comb generator (OFCG) is employed as the multi-wavelength optical source followed by a wavelength MUX where COMB lines can be divided into individual DWDM channels. Each channel is modulated by an intensity modulator (IM) respectively. In the downstream, quadrature phase shift keying OFDM (QPSK-OFDM) signal is converted to optical domain. An optical multiplexer (MUX) is employed to combine the DWDM channels with signal sent into the 25.6 km single mode fiber (SMF) for downstream transmission. At the optical network unit (ONU) side, direct detection (DD) receiver is adopted taking into account the cost of ONU. For upstream link transmission, the OFDM downstream signal is re-modulated by another intensity modulator at 2.5-Gbit/s OOK format at the ONU and transmitted back to the OLT.

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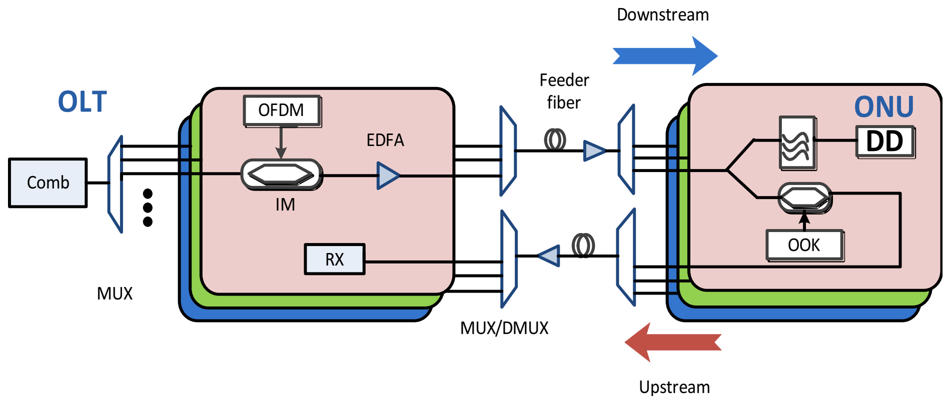


Figure 1: Illustration of the ultra-dense OFC based DWDM-OFDM-PON system. OLT: optical line termination, EDFA: Erbium-doped fiber amplifier, IM: intensity modulator, DD: direct detection, RX: receiver.

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In our experiment, a comb generator using one IM and a DPMZM with only two microwave driving sources is firstly realized. This scheme is a relatively simple and low-power consumption solution for OFC generation in which high power RF signal sources and specially tailored waveforms are not used. The OFCG scheme is shown as Figure 2. A narrow linewidth continuous wave (CW) operated laser source is employed as the input signal. A dual-parallel Mach-Zehnder modulator (DPMZM) is used as the first stage OFC operated in Push-Pull configuration. 2 first order sidebands are generated by the upper arm biasing at null transmission point and the other three lines are excited by the lower arm operating at maximum point of the transmission curve. With the superposition of optical field of both arms, 5 comb lines are generated at point a in Figure 2. The DPMZM is followed by another MZM working as the second stage. The bias voltage of the second stage IM is adjusted at the point which leads to an equation of amplitude of carrier and first order sidebands. In that condition, the second order sidebands can be effectively suppressed. For any one wavelength from those 5 comb lines, the modulated output through IM can be expressed as:

$$\begin{aligned} E_{out3}(t) &= E_{in3}(t)\left[\cos\Phi_{\mathrm{DC}}J_0(m_3)\cos(\omega_0 t)+\sin\Phi_{\mathrm{DC}}J_1(m_3)\sin\left(\omega_0+\omega' t\right)\right.\\ &\quad \left.-\sin\Phi_{\mathrm{DC}}J_{-1}(m_3)\sin\left(\omega_0-\omega' t\right)\right] \end{aligned} \tag{1}$$

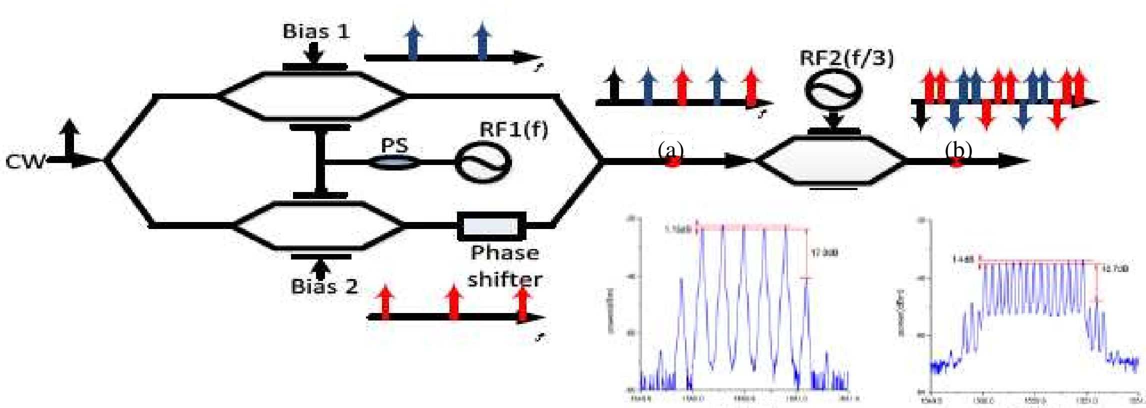


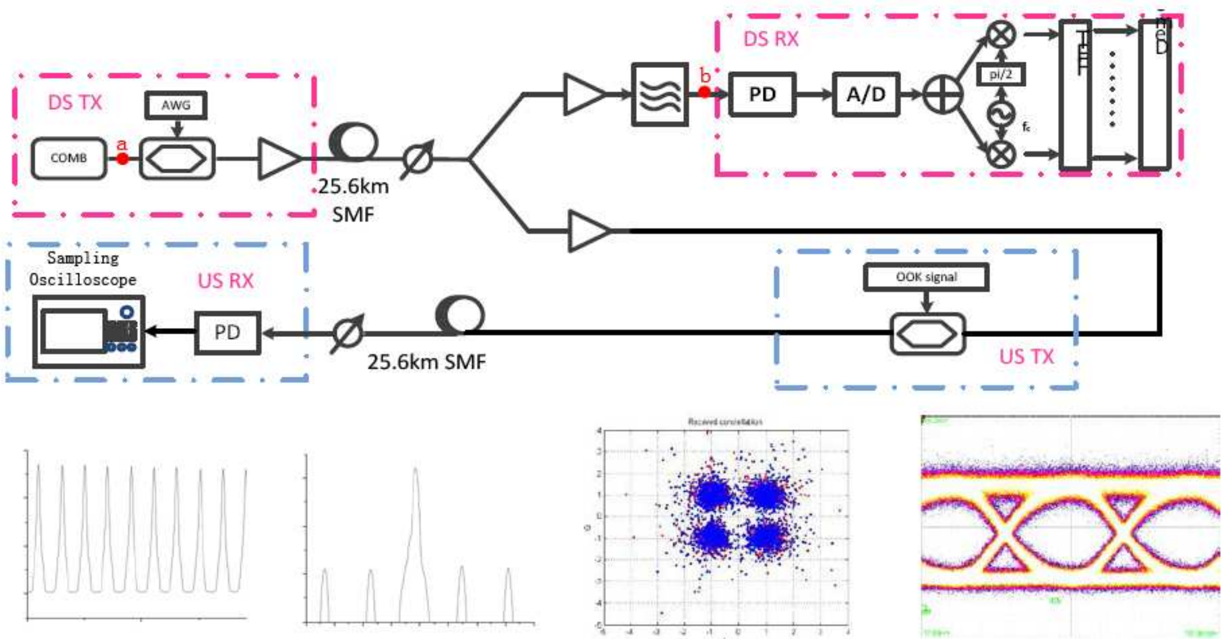

Figure 2: Experimental setup for the OFCG composed of one DPMZM and an MZM and the spectrum generated at point (a) and (b). (CW: continuous wave laser, RF: radio frequency, PS: 50 : 50 power splitter).

If we set $\omega' = \omega/3$ and let

$$\cos\Phi_{\mathrm{DC}} J_0(m_3) = -\sin\Phi_{\mathrm{DC}} J_1(m_3) \tag{2}$$

A single line will evolve into three with equivalent amplitude. Therefore, a spectrum of 15 comb lines with equal power can be generated with the spectral spacing as one-third frequency of the first stage comb.

With the proposed OFCG, 10 channels with 25 GHz spacing is provided at the transmitter. 10-Gb/s baseband QPSK signal is generated off-line with 64 subcarriers and a fast Fourier transform (FFT) size of 256 and a cyclic prefix (CP) of 0.1. The off-line signal was uploaded into arbitrary waveform generator (AWG, Tektronix AWG 7122), and a Mach-Zehnder modulator was employed to convert the OFDM signal to DSB optical signal. All the channels are modulated simultaneously. Optical distribution network was emulated with 25.6 km single mode fiber (SMF) and a variable optical attenuator. The downstream signal was photodetected using a PD, and sampled by a 50 GS/s Tektronix real-time scope. Demodulation and Bit Error Rate (BER) counting were implemented offline. Instantaneous multi-wavelength loading OFDM-QPSK signal is performed through direct modulation on the generated OFC. The constellation map shown in Figure 3(c) is acceptable in the case of simulating the PON transmission environment. And simultaneously multi-wavelength OOK modulation and transmission was also verified, the eye-diagram of the upstream with 2.5-Gb/s OOK after 25.6 km is displayed in Figure 3(d).




(a) (b) (c) (d)

Figure 3: Experimental setup of the proposed DWDM-OFDM-PON system. The optical spectrum is measured at the corresponding point (a) and (b). Constellation map of downstream QPSK-OFDM signal in PON transmission environment (c) and eye-diagram of the 25.6 km transmitted upstream 2.5-Gb/s OOK signal with multi-carrier simultaneously modulation is displayed as (d). AWG: arbitrary waveform generator; A/D: analog to digital; PD: photo diode.

We proposed and demonstrated an ultra-dense optical comb based DWDM-OFDM-PON system. A simple and cost-effective OFCG consists of a DPMZM and an IM is posed for providing multiple channels with reconfigurable wavelength spacing for ultra-dense WDM-PON based access network. For the downstream, OFDM signal with multi-level modulation was encoded into OFC lines to enhance the spectral efficiency. And the OFDM signal would be remodulated by OOK data for uplink transmission for its ease implementation in ONU. We experimentally demonstrated the OFCG. 10 optical carriers with 25 GHz spacing were modulated by 2.5-GB/s QPSK-OFDM for the downlink signal transmission. It is beneficial to investigate the OFDM-PON system for seamless integration of wired-and-wireless communication system.

## ACKNOWLEDGMENT

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