AMO-OFDM Signal Delivery of 20 Gbit/S throughput in 20-Km Single Loopback Fiber Link Employing Baseband I/Q Separation

Adaptive Optical OFDM Modulation and Separate I/Q Baseband Signal Transmission with Remotely-fed RSOAs for Colorless ONU in Next-generation WDM Access

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Abstract: We demonstrated a novel scheme to transmit 20-Gb/s adaptively modulated optical orthogonal frequency division multiplexed (AMO OFDM) signal employing separate in-phase (I) and quadrature (Q) channel baseband delivery in a 20-km single loopback fiber link based on 1-GHz reflective semiconductor optical amplifiers (RSOAs) for a colorless optical network unit (ONU). Adaptive loading process was applied to the OFDM signals to overcome the bandwidth limitation of RSOAs. The I and Q channel data streams in the OFDM signals were separately carried on individual optical carriers with different wavelengths without Hermitian Symmetry for baseband transmission. Our proposed scheme was experimentally demonstrated using a periodic property of free spectral range (FSR) in a wavelength multiplexer. The separated optical "dual" carriers were provided by the same port of a wavelength multiplexer to reduce the number of used WDM channels for a upstream.

1 INTRODUCTION

Wavelength division multiplexed passive optical network (WDM PON) has been one of the most attractive candidates to satisfy explosive growth of required bandwidth as well as to provide various advantages for next-generation access networks, such as transparency of data format, robust security, and ease of maintenance and upgrading. Its key challenging issue has been to reduce its inventory cost, especially in realizing optical network units (ONUs). A colorless ONU is inevitable for this issue because the same transceiver can be used regardless of the wavelength. A reflective semiconductor optical amplifier (RSOA) is a good example so has been proposed in many reports, but it is bandwidth-limited (Lee et al., 2006).

Many technologies have been proposed to deal with this issue and can be categorized as follows: using electrical equalization (Papagiannakis et al., 2008) and a specifically designed RSOA module and its driving circuit (Cho et al., 2011); (Valicourt et al., 2011). Electrical equalization techniques are susceptible to chromatic dispersion and require optical filter detuning with optical devices. It is imperative to use complicated design techniques to fabricate the RSOA module and its circuit to carefully tune its electrical frequency response. In addition, most of the proposals are based on a locally fed RSOA or demonstrated in optical back-to-back link to avoid Rayleigh backscattering and therefore, they are far from practical scenarios.

Orthogonal frequency division multiplexing (OFDM) with multi-level modulation has been widely used due to its high-spectral efficiency in overcoming bandwidth limitation of the RSOA. It is also robust to chromatic dispersion because the OFDM symbol duration is longer than single carrier modulated case in which the data is parallel-distributed into multiple subcarriers. Optical OFDM with direct-detection has been preferred for access networks because of cost effectiveness (Schmidt et

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al., 2008).

In this paper, we experimentally demonstrate a novel 20-Gb/s adaptively modulated optical OFDM (AMO OFDM) transmission scheme over 20-km single fiber loopback link employing bandwidth limited RSOAs as colorless ONUs. The in-phase (I) and quadrature (Q) channels are separated in two different wavelengths and transmitted at baseband. The optical carriers for upstream I/Q channels are generated at an optical line terminal (OLT) and delivered through the 20-km bi-directional link. In the proposed scheme, these wavelength channels have a free spectral range (FSR) spacing of an arrayed waveguide grating (AWGR) to reduce the number of use WDM-PON channel. Therefore, these "dual" channels could be transmitted through the same port of an AWGR.

2 SYSTEM DESIGN

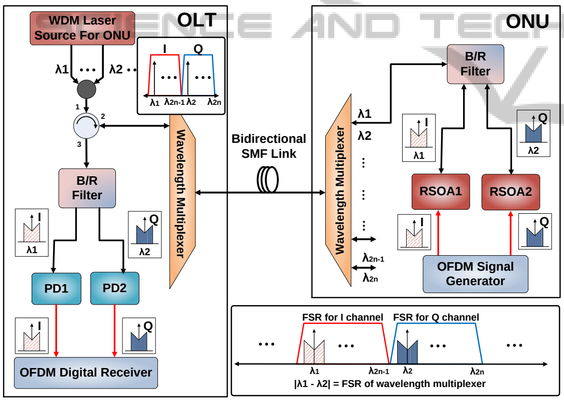

Figure 1: Proposed optical OFDM/WDM PON using separated I/Q baseband delivery for colorless ONU.

Figure 1 briefly shows the proposed optical OFDM/WDM-PON system. The adaptive bit and power loading for each OFDM subcarrier, is used to overcome the bandwidth limitation of the RSOAs. This adaptive loading is based on evaluated error vector magnitude (EVM) in term of the "probe" signal for each subcarrier. This EVM converts to the signal-to-noise ratio (SNR) and apply to the bit/power loading algorithm (Chow et al., 1995). Then, the OFDM signal is divided into real and imaginary value for I and Q channel in the time domain, and each channel signal drives the RSOA 1 and 2, independently. Two continuous wave (CW) signals has difference wavelength in OLT are fed to the RSOA 1 and 2 in ONU. These CW signals work as "dual carriers" for upstream signals. The wavelength spacing between dual carriers depends on FSR of AWG because they are required through the same port of AWG. Each carrier is modulated by the I/Q channels of the OFDM signal at RSOA 1 and 2, independently. After the modulation at RSOAs, the dual carriers are combined at blue/red (B/R) filter which works as red and blue band separators or combiner, and transmitted to the OLT through a single mode fiber (SMF) link. The receiver consists of two photo detectors (PDs) for receiving dual channel carriers. Received I and Q channel signals are combined and recovered at digital receiver for OFDM signal. This scheme should need the training sequence (TS) because time synchronization mismatch between the I/Q channels could be occurred. The TS was compared to received data stream and find the start point of the I and Q channel frames, independently.

3 EXPERIMENTAL SETUP, RESULTS AND DISCUSSIONS

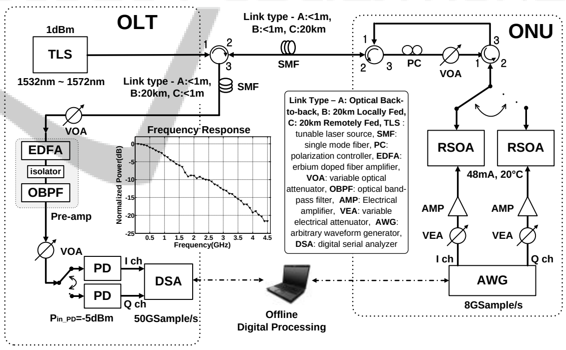

Figure 2: Experimental setup.

Figure 2 represents the experimental setup of the proposed scheme. The CW optical source was realized by a tunable light source (TLS) at 1532 to 1572 nm wavelengths and optical power of 1 dBm. This CW seed light was launched into an RSOA through a 20-km SMF link. The RSOA was operated at the bias current of 48 mA and temperature of 20°C. Their 3-dB electrical bandwidth was less than 1 GHz as shown in inset of Figure 2. The adaptively loaded OFDM signal was generated by MATLAB® and extracted from an arbitrary waveform generator (AWG) sampling at 8 GSample/s. This extracted OFDM signal consists of real-valued data streams of the I and Q channels. The number of FFT size was set as 1024. The occupied bandwidth was 4 GHz, range from DC to 4 GHz. An electrical amplifier and variable electrical attenuator (VEA) were used for full modulation of the RSOA. Modulated optical signals from the RSOA were transmitted through 20-km SMF link. A preamplifier was realized by employing an erbium-doped fiber amplifier (EDFA) and optical bandpass filter (OBPF) to enhance the receiver sensitivity. This whole process was consecutively repeated for counterpart of the previous channel in different wavelength. For example, the Q channel part of the baseband OFDM symbol was consecutively transmitted and recovered after doing the same process for the I channel part of the baseband OFMM symbol. The received two channel electrical signals were sampled by a digital serial analyzer (DSA) at 50-GSample/s sampling speed. Then, these signals were digitally combined to construct the complex-valued OFDM symbol and evaluated by an offline process from MATLAB®.

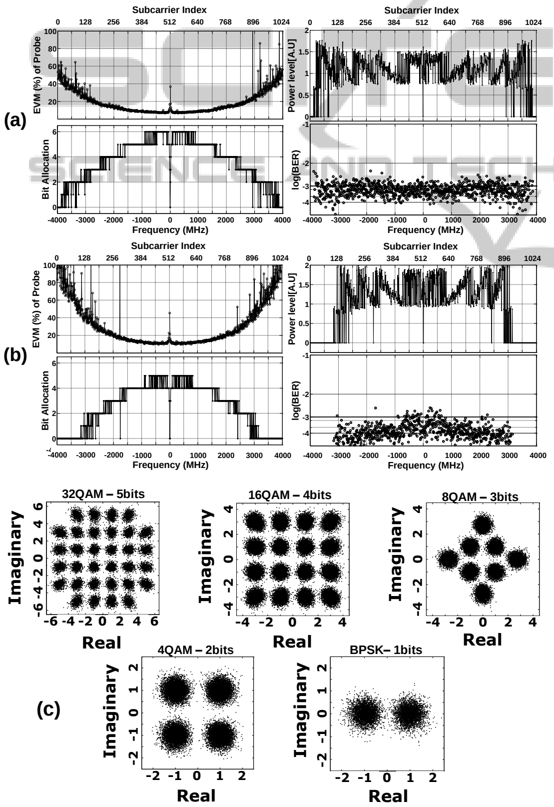

Figure 3: Probe EVM, adaptive bit and power loading profile, BER each data subcarrier and constellation of maximum bit loading subcarriers: (a) optical back-to-back (data rate: 29.68 Gb/s, average BER: $9.79x10^{-4}$, (b) 20-km bi-directional (data rate: 21.59 Gb/s, average BER: $4.57x10^{-4}$); (c) recovered signal constellation for the 20-km bi-directional case.

In first, a "probe" signal with the uniform bit and power allocation of 16 quadrature amplitude modulation (QAM) was transmitted to evaluate the channel response. The SNR converted from evaluated EVM was used to decide the response of each subcarrier. According to this response, adaptive bit and power loading were applied to each OFDM subcarrier. Figure 3 (a) and (b) represent the evaluated EVM of probe signal, the adaptively loaded bit and power allocation profile, bit error rate (BER) performance for each OFDM subcarrier, and constellation of maximum bit loading subcarriers in optical back-to-back and bi-directional 20-km transmission, respectively. These results verified that more bit were allocated at subcarriers of lower EVM and less bit were allocated at subcarrier of higher EVM of probe signal. The pre-emphasis values depended on difference between real number value and round number for realistic bit loading of bits. Compare to the optical back-to-back, some subcarriers at high frequency region allocated zero bits because the EVMs at these subcarriers were not enough to transmit even a one bit.

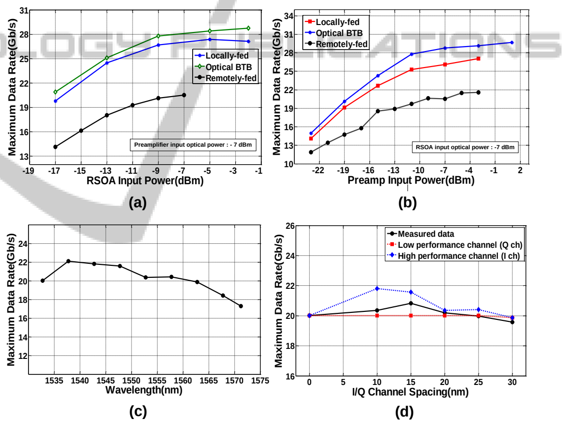

Figure 4: Maximum achievable throughput as a function of: (a) input optical power of the RSOA, (b) input optical power of preamplifier, (c) various wavelength, (d) I/Q channel wavelength spacing.

Figure 4 (a) and (b) represent the maximum achievable data rate with the input optical power of the RSOA and the preamplifier for optical back-to-back, 20-km unidirectional (locally-fed), and 20-km bi-directional (remotely-fed) cases. The 20-km bi-directional transmission system supports higher than 20 Gb/s at upper the -10 dBm RSOA input optical power and -11 dBm preamplifier input optical power as shown Figure 4 (a) and (b). This system has about 6 Gb/s penalty compare to the 20km unidirectional case. This degradation was mainly come from the Rayleigh backscattering noise. The maximum achievable data rate for all cases is measured with BER < 10^{-3}.

The maximum achievable data rate with various wavelength and spacing also measured to verify colorless operation and applicability of the FSR periodicity of AWG as shown in Figure 4 (c) and (d). The measured optical carrier range from 1532.5 nm to 1572.5 nm (equivalent to almost entire C band), the maximum achievable data rate was maintained almost 20 Gb/s at the RSOA and preamplifier input optical power of -7 dBm and -3 dBm, respectively. This maximum achievable data rate slightly decreased at about 1570 nm because gain characteristic of EDFA in preamplifier has poor gain characteristic at this wavelength. For this reason, the optical receiver sensitivity also became worse and led to the performance penalty. The I/Q wavelength difference has no influence on the maximum achievable data rate as shown in Figure 4 (d). These data rates are similar to the average of low and high wavelength channel performance.

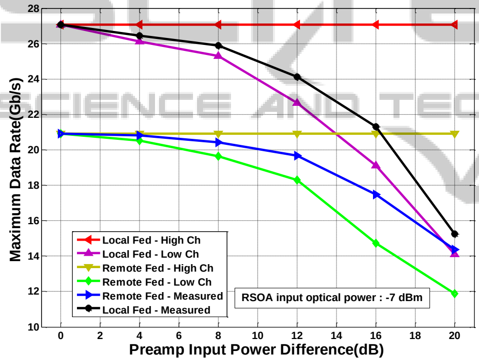

Figure 5: Maximum achievable data rate with various input optical power deviation of the preamplifier power between I /Q channels.

The signal performance was also evaluated as a function of the input preamplifier power deviation between I/Q channels as represented in Figure 5. In this figure, “high” channel means either I or Q channel which had higher input optical power at the preamplifier, and vice versa. The measurement curves labeled “measured” represents the signal performance after combining I/Q channels (in other words, “high” and “low” channels) with a given input preamplifier power deviation. It was verified that the signal performance was degraded as the power deviation was increased. As a whole, the performance degradation followed the “low” channel’s characteristic. However, this performance degradation was almost negligible when the deviation was less than 12 dB, which led to 1-Gb/s performance penalty compared to the case of no power deviation. This 12-dB deviation margin was high enough to provide consistent data rate transmission in the proposed scheme because both I/Q channels indeed shared the same link and consequently, there was no significant input preamplifier power difference between I/Q channels.

4 CONCLUSIONS

We successfully demonstrated the novel transmission scheme to provide 20-Gb/s optical OFDM signal through the 20-km SMF based on the 1-GHz bandwidth-limited RSOAs for source free and colorless ONU. The I and Q channels were separated in wavelength domain and independently transmitted at baseband without Hermitian Symmetry. The CW optical sources for upstream signal were generated at OLT pass through bi-directional link for source free ONU. We reported a proof-of-concept experiment to show the applicability of FSR periodicity of AWG. The OFDM symbol with adaptive bit and power loading was applied to overcome the bandwidth limitation of the RSOA. This solution is promising for low-cost 20 Gb/s upstream transceiver for colorless ONU of >10G-PON.

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