Chirped RSOA Modulation by Using Adaptive OFDM for Long Reach WDM-PONs

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Abstract— **We theoretically and experimentally characterize the non-negligible power fading in OFDM signaling due to the chirping effect of RSOA. To minimize the power fading, we use power pre-emphasis in OFDM signal. We experimentally investigate this approach in a high speed (10 Gb/s) long reach (60 km) transmission system by using a commercially available RSOA of <1.5 GHz modulation bandwidth. By this technique we achieve a sensitivity improvement of 5dB. The results presented here are useful to design high speed RSOA based next generation long reach WDM-PONs.**

Keywords-Orthogonal Frequency Division Multiplexing (OFDM), Reflective Semiconductor Optical Amplifier (RSOA), Passive Optical Networks (PONs).

I. INTRODUCTION

Reflective semiconductor optical amplifier (RSOA) based WDM-PONs has been considered to be a most promising candidate for next generation access networks. However, commercially available RSOAs have a limited electro-optical modulation bandwidth (~1GHz) which significantly restricts their application to 10 Gb/s PON system. On the other hand, baseband adaptive OFDM, also called Discrete Multi-Tone (DMT) modulation shows a number of excellent features, for example, inherent robustness against the fiber chromatic dispersion, flexibility to allocate data among different subcarriers and above all, high spectral efficiency. This technique is therefore suitable to be used to increase the data rate in bandwidth limited optical devices like RSOAs. Therefore, DMT modulation for RSOA based colorless ONUs could provide a cost effective way to design high speed 10 Gb/s WDM-PONs [1],[2].

However, RSOAs have considerable frequency chirp, which results in the power fading in the optical double sideband signal generated by direct modulation in fiber transmission. RSOA chirp is one of the most important limiting factors in OFDM transmission; not only it reduces the transmission distance but also reduces the system achievable maximum capacity [3]. In earlier DMT investigations this chirp induced fading effect has not been considered, especially to design a long reach access network [1],[2].

Here we investigate both theoretically and experimentally the impacts of RSOA chirp on the overall system performance. To overcome the RF fading, we propose to use the pre-emphasis power loading in OFDM modulation. A similar pre-emphasis has been already investigated to overcome system impairments in conventional direct-detection optical OFDM system [4]. However, previous analysis neither considered the chirping effect nor included the limited bandwidth response typical of RSOA modulation. We demonstrate the operation of 10 Gbit/s transmission by using commercially available RSOA having a bandwidth <1.5 GHz over 60 km of single mode fiber without any dispersion compensation. By applying the pre-emphasis, we are able to recover up to 5 dB in receiver sensitivity (within the FEC BER).

The paper is organized as follows. Section II provides a theoretical study of pre-emphasis technique and fading effect from RSOA chirp. Section III presents the experimental setup and results. Finally, Section IV summarizes the paper.

II. PRE-EMPHASIS POWER IN CHIRPED RSOA-OFDM MODULATION

Direct modulation of an optical carrier by an OFDM signal results into a double-sideband optical signal, which is subject to RF power fading when transmitted through a dispersive fiber. Neglecting the transmission losses, the RF power fading can be represented as:

$$P_{rf}(f) \propto \cos^2(2\pi^2 \beta_2 L f^2) \quad (1)$$

where β_2 is the group velocity dispersion (GVD) parameter, L is the fiber length, and f is the frequency. When considering the chirp effect, Eq. (1) is modified as [5]

$$P_{rf}(f) \propto (1+\alpha^2)\left|\cos^2(2\pi^2 \beta_2 L f^2 + \tan^{-1}\alpha)\right| \quad (2)$$

where α is the chirp parameter. Fig 1(a) shows the theoretical RF gain curves for different values of chirp parameters for propagation over a length of 25 km through a Single Mode Fiber (SMF). As expected, the fading dip moves

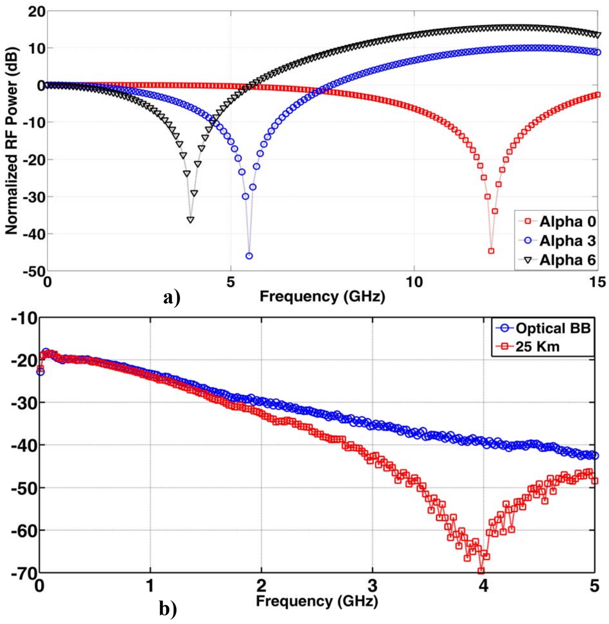

Figure 1: a) Theoretical fading curves with different alpha values; L= 25km b) Measured frequency response of RSOA based system

towards the DC as the chirp parameter increases even with a small span of fiber. For 10 Gb/s long distance transmission using RSOA-OFDM modulation, the fading effect is much more detrimental. The limitation mainly comes from the RSOA device itself as it has very low 3dB bandwidth (<1GHz) and also a high chirp parameter.

In order to overcome this limitation, the pre-emphasis power can be an effective method. After direct detection, the received optical signal with pre-emphasis power can be expressed by [3]:

$$I \cong 1+2\sqrt{1+\alpha^2}\sum_{n=1}^{N}\kappa_n x_n \cos(n\omega t+\theta_n)\cos(n^2\theta_d-\theta_\alpha) \qquad (3)$$

where, x_n and θ_n are the amplitude and phase of n^{th} subcarriers, θ_d and θ_α are the phase variation due to fiber dispersion and modulator chirp respectively. The κ_n values are the pre-emphasis coefficients that can be evaluated as the inverse of the measured channel SNR i.e., κ_n = SNR_n^{-1}. The alpha parameter of the RSOA under use can also be determined from Eq. (2), according to:

$$\alpha = \tan\left(\left|2\pi^2\beta_2 L f_{Null}^2 - \pi/2\right|\right) \qquad (4)$$

The f_{Null} is the first null frequency. The figure 1(b) shows the experimentally measured frequency response of the RSOA, which gives the null frequency at 4 GHz. By using (4), the alpha parameter of the RSOA is calculated to be 5.67. We will use this value in equation (2) which will yield the SNR of each subcarrier. Finally, the required pre-emphasis power coefficients can be estimated from the measured SNR.

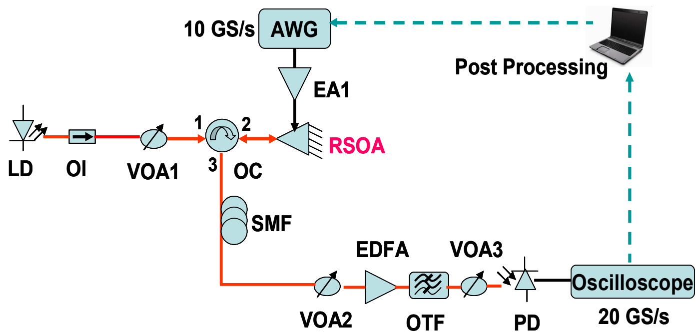

Figure 2: Experimental Setup

III. Experimental Setup and Results

In order to evaluate the performance in long distance PONs, we realized the experimental setup illustrated in Fig. 2. Followed by the CW optical source, there were also an optical isolator (OI), a variable optical attenuator (VOA1) and an optical circulator (OC). The VOA1 was used to control the input seeding power of RSOA. The modulated signal was passed through the 60 km single mode fiber (SMF). The RSOA used in this experiment is a commercially available device (CIP SOA-RL-OEC-1550). It was operated with a bias current of 60 mA and temperature of 20ºC. Under this condition, the measured 3dB bandwidth was 0.96 GHz (see Fig.1(b)). The device has small signal gain of 20 dB and a saturated output power of 3 dBm. The OFDM signal was constructed offline and then uploaded to a 5 GHz, 10 GS/s Arbitrary Waveform Generator (AWG). The signal was composed by 256 subcarriers (the first carrier has no power). The real signal was generated by taking the complex conjugate of 256 subcarriers. Finally, the RSOA was directly modulated by the OFDM signal. A pre-amplified optical receiver was used for this long distance transmission. This was composed by an EDFA, an optical tunable filter (OTF) of 25 GHz bandwidth, two VOAs and a 14 GHz PIN photodiode. Once received, the electrical signal was sampled by a 20 GS/s real time digital oscilloscope. Figure 3(a) shows the theoretical channel gain by using equation (2) for 60km fiber transmission and α parameter of 5.67. Also the Fig. 3(b) shows the experimentally measured SNR from Error Vector Magnitude (EVM) by using BPSK in all the carriers with equal power. The baseband bandwidth of OFDM signal was set to 2.5 GHz, this also avoids the frequency dip at 2.6 GHz. Both the results have good agreements, showing around 20 dB SNR degradation after 2.5 GHz. The Fig. 3(b) also shows the resulted improved SNR for the high frequency subcarriers after applying the pre-emphasis power as the inverse of the

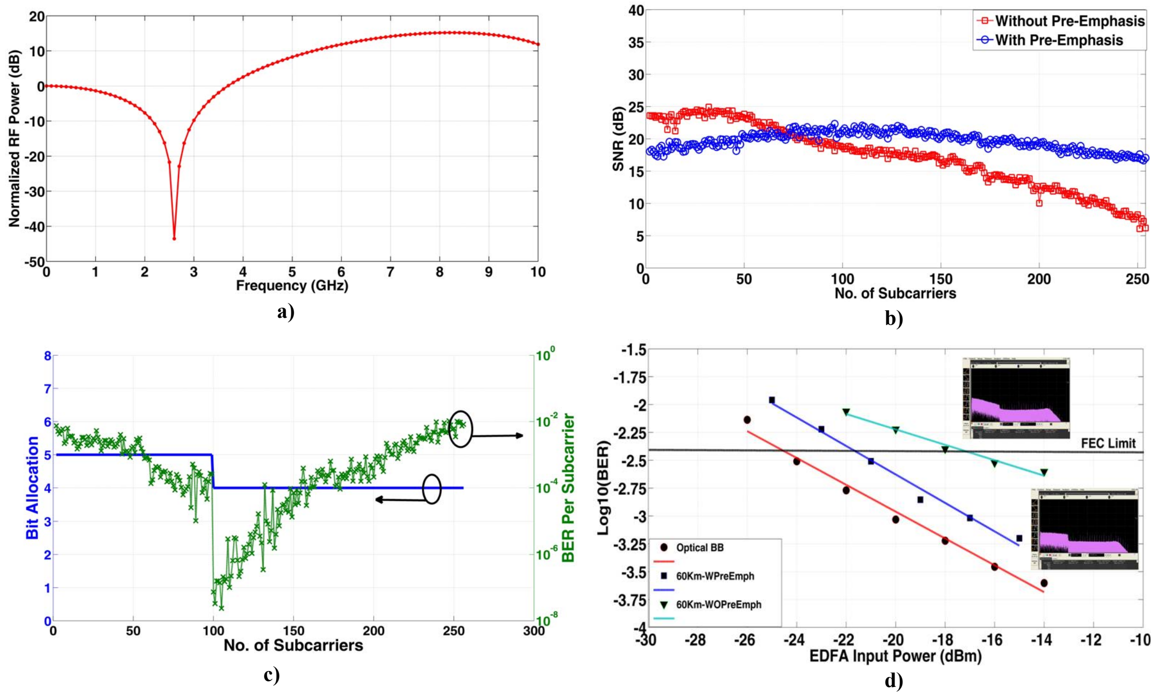

Figure 3: a) Theoretical RF Gain for L = 60km and α= 5.67; b) Measured SNR with pre-emphasis and without pre-emphasis after 60 km; c) Bit allocation for each carrier with corresponding BER ; d) BER performance; Insets shows the power spectral density of OFDM signal with pre-/wo-pre emphasis power.

measured SNR. The optimized system shows a more uniform SNR behavior (only around 6 dB fluctuation) and a significant increase of SNR in the region of fading dip. To achieve the 10 Gb/s transmission by maintaining the required BER within FEC limit (3.8e-3) [6], the corresponding bit allocations are shown in Fig. 3(c). The gross data rate based on this allocation is 10.96 Gb/s. By considering the overhead (7% for FEC overhead [6] and 3% for training sequence with cyclic prefix), the net data rate will be 9.96 Gb/s over the 60 km fiber transmission. The Fig. 2(c) also shows the BER performance per subcarriers which ensure BER < 2e-3. Finally, the BER performance as a function of receiver sensitivity was measured for optical back to back, with pre-emphasis and without pre-emphasis conditions. The PD input power was set to 0 dBm. The RSOA input power was maintained to -5 dBm for having a better SNR even after this long distance transmission [7]. As shown in Fig. 3(d), by using pre-emphasis power allocations, there was around 5 dB improvement of the receiver sensitivity (measured at the FEC limit) compared to a non-equalized OFDM transmission. The possible reason of penalty from optical back to back is due to the presence of Subcarrier-Subcarrier Intermixing (SSI) product that are intensified by additional chirp of RSOA after the fiber transmission [3]. As these mixing noise components are mostly concentrate near DC, a placement of Guard Interval (GI) from DC can overcome the limitation. However, it may not be a good choice due to the limited bandwidth of RSOA itself.

IV. CONCLUSIONS

We experimentally demonstrated the feasibility of pre-emphasis power allocation technique for 10 Gb/s transmission over 60 km fiber span in chirped RSOA based access system. The result shows an improved performance compared to flat power allocation in the presence of RF fading.

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