Downstream Modulation Index Tuning to Enable Full-duplex OOK-DL/OFDM-UL Transmission in RSOA-based Radio-over-Fiber System

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***Abstract* — In this paper, we investigate the possibility of transmitting full-duplex digital and analog signal in a self-seeding, re-modulating Radio-over-Fiber (RoF) system based on reflective semiconductor optical amplifier (RSOA). We study the effect of tuning the modulation index of the On-Off-Keying Downlink (OOK-DL) signal on its reception performance and the amplitude modulation erasing in RSOA. By properly selecting operating conditions, downlink residual modulation on the reflected optical carrier can be minimized to allow the transmission of a WiFi Orthogonal Frequency Division Multiplexing Uplink (OFDM-UL) signal. We experimentally demonstrate bidirectional transmission over 20km of standard single mode fiber (SSMF) and show an operational region where we can achieve error-free for a 1Gb/s OOK-DL signal while we remain below forward error correction (FEC) threshold for WiFi OFDM-UL using QPSK, 16QAM, and 64QAM modulation modes.**

Keywords—Full-duplex, Radio-over-Fiber, RSOA, self-seeding WDM-PON, optical wireless communication, modulation erasing

I. INTRODUCTION

Recently, there have been many studies and developments in bringing the fiber closer to subscribers such as fiber-to-the-home (FTTH) networks [1]. In order to accommodate a wide range of wireless services at low cost, the idea of fiber-to-the-antenna (FFTA) is attractive yet challenging [2]. In this architecture, wireless signals received from an antenna are transmitted through the fiber as analog signal without performing analog-to-digital conversion (ADC). This results in a low cost, low power-consumption remote antenna node (RAU) at the user end (UE) with all the costs transferred to the central office (CO) where power and resource allocation are more easily managed.

Wavelength division multiplexing passive optical network (WDM-PON) is the key architecture for implementing optical access networks between the CO and many UEs [3]. Usually, 2 laser sources are required to transmit downlink (DL) and uplink (UL) data between CO and UE. However, based on RSOA, self-seeding WDM-PON systems that utilize only one laser source at the CO have been intensively studied [4-11]. At the optical network terminal (ONT), or UE, a saturated RSOA is employed to erase the amplitude modulation of the DL stream and reflect back the optical carrier. The RSOA can be directly modulated by applying a signal to its driving currents. Therefore, the reflected carrier can be re-modulated with UL signal and transmitted back to the CO in the same fiber. However, due to the residual modulation from the DL signal that interferes with UL performance, many RSOA-based WDM-PON systems employ phase modulated DL signals [6], or different spectral locations for DL and UL [7], and the UL signal is usually in OOK format. In RoF systems using the same architecture, the problem of residual modulation of OOK-DL is too severe to support analog signal transmission [8]. Some studies proposed using 2 separate fibers [9], transmitting pass-band signals [10], or time-division multiplexed DL and UL signals [11]. These schemes, which require sophisticated receivers for DL signals, are difficult to implement in a real system at low-cost RAU.

Single fiber transmission of OOK signals for both DL and UL in a self-seeding, re-modulating scheme can be possible if the extinction ratio of OOK-DL signal is properly controlled as in [10 - 12]. The modulation index of OOK-DL was kept small to assist the amplitude modulation erasing in a gain saturated SOA. The OOK-UL signal is normally sent at a high modulation index and lower baud-rate to be distinguishable from the residual DL-crosstalk. With this technique, transmission up to 40 km of SSMF was achieved. However, to the best of our knowledge, no study has been done to investigate the performance of full-duplex digital-DL and analog-UL signals in RSOA-based RoF systems.

In this paper, we measure the modulation erasing of the RSOA using different conditions for OOK-DL signal in a back-to-back (B2B) case. Then, we fix the transmission length at 20 km, transmit 1Gb/s OOK-DL simultaneously with a 10MHz WiFi OFDM-UL signal down-converted to an intermediate frequency (IF) of 30MHz, and measure their performance as a function of bias voltage (V_{bias}) and the swing of modulating signal (V_{RF}) of the DL signal. The experimental

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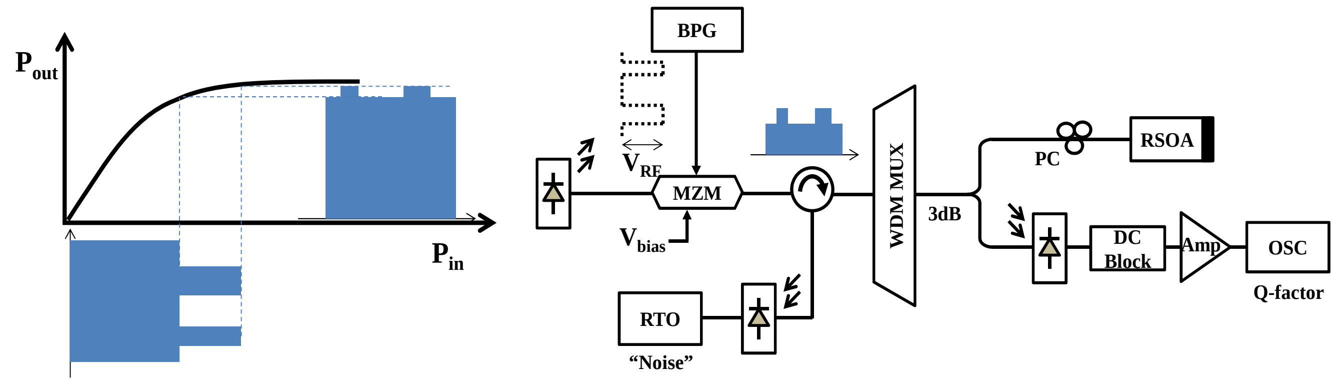

Fig.1. Modulation index compression in saturated SOA (left); Experimental setup to investigate effect of OOK-DL modulation index on received Q-factor and noise variance of reflected carrier (right).

results show an optimal condition and a wide operational region in which we obtain error-free for OOK-DL and below FEC threshold for OFDM-UL with all modulation modes.

II. Working Principle

The amplitude modulation erasing is based on the gain compression effect that occurs when an SOA is operating in its saturated regime as shown in fig. 1 (left). If the OOK input signal has a low modulation index and the optical carrier power is kept high enough to saturate the SOA, the gain distributed to "1" and "0" levels are nonlinear, resulting in the suppression of level "1" and the modulation index reduction of the output signal. The average power of the input signal plays an important role in the compressing effect because it defines the saturation points in the SOA. Detailed analysis of DL bit pattern cancellation in saturated linear SOA was studied in [12]. For a better understanding of the amplitude modulation erasing in RSOA to accommodate an OFDM-UL signal, we carry out a B2B experiment, depicted in fig. 1 (right). We measure the "noise" on the reflected optical carrier and the degradation of the OOK-DL signal by varying V_{bias} and V_{RF} of the Mach-Zehnder modulator (MZM) at the DL transmitter. The OOK-DL signal is generated by modulating a continuous wave (CW) from a laser source with an electrical PRBS 2^{31} - 1 bit pattern at 1 Gb/s. V_{π} of the MZM is about 5V. V_{bias} and V_{RF} are tuned independently to vary the signal conditions. This allows us to cover a wide variety of amplitude modulation (AC) and optical carrier (DC) in the output signal. The signal propagates through a circulator and is devided by a 3dB splitter. One path goes to the photo-receiver, the DC component of the electrical signal is rejected while its AC is amplified and captured by a 20GHz sampling oscilloscope (OSC). The other path passes through a polarization controller (PC) and then in the RSOA its modulation is suppressed. The reflected optical carrier propagates back and is directed to another photo-receiver. Both of its AC and DC components are acquired by an 8GSa/s real-time scope. We use the Q-factor measurement to examine the performance of the OOK-DL signal. For the reflected carrier, we use the histogram function to measure the standard deviation of the AC component on the acquired trace which shows the 1Gb/s modulation residual that is considered the main "noise" source of the UL signal.

Fig. 2 shows the measured noise standard deviation of the AC component on the reflected carrier while V_{bias} and V_{RF} are adjusted from 0.2 to $0.8V_{\pi}$ and 0.01 to $0.6V_{\pi}$ respectively. With

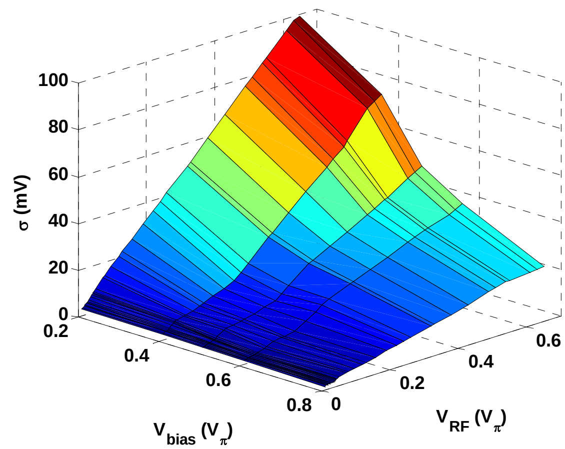

Fig.2. Standard deviation of residual modulation on reflected optical carrier as a function of V_{bias} and V_{RF}

this, we can obtain an OOK modulation index from 2.5 to 80% in various conditions where different CW powers are sent to the RSOA. At any fixed V_{bias}, the noise amplitude is negligible when V_{RF} is considerably small and increases quite linearly proportional to V_{RF}. Figure 2 shows that the slope increases as V_{bias} decreases. To stay in harmony with the RSOA's erasing efficiency at different saturation points V_{RF} should be as low as possible. When V_{RF} is fixed and V_{bias} is varied, the noise's standard deviation increases faster at lower V_{bias}. In fig.1 (left), the saturation of the RSOA is mainly defined by the input signal's DC component which is controlled by V_{bias}. Low V_{bias} lets the RSOA work in linear regime and significantly reduces the erasing effect. Therefore, V_{bias} is expected to be an important factor in defining a proper working condition for OFDM-UL signal.

For all of these operation points, the measured Q-factor of the OOK-DL signal is always above 6dB which corresponds to a bit error rate (BER) of 10^{-9}. This is an encouraging factor showing the robustness of the OOK signal which assures good performance even when it has very low modulation index. When V_{bias} is set so that the MZM is operating in linear regime, V_{RF} plays the key role in defining the modulation index:

$$MI = V_{RF}/(2V_{bias}) \quad (1)$$

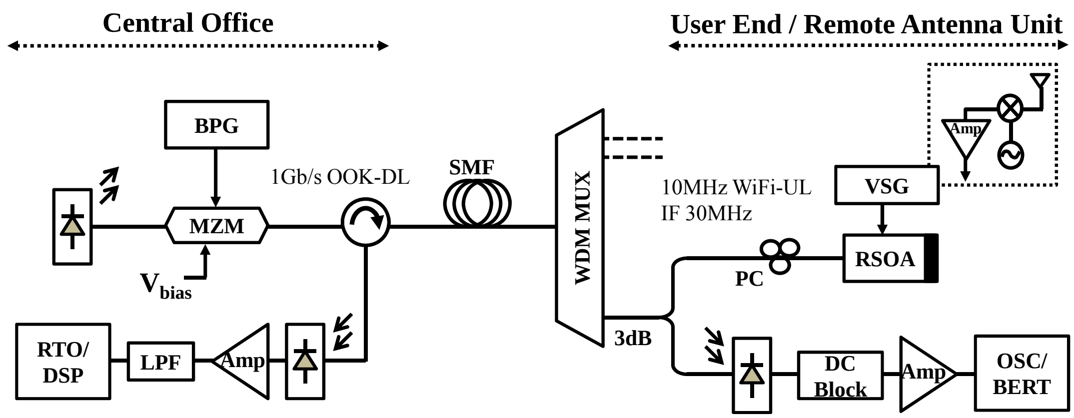

Fig.3. Modulation index compression in saturated SOA (left); Experimental setup to investigate effect of OOK-DL modulation index on received Q-factor and noise variance of reflected carrier (right).

Therefore, it mainly affects the Q-factor of the DL. When a transmission link is introduced, the operational region for OOK-DL is narrowed toward higher V_{RF} and V_{bias}. By keeping a proper V_{bias} and tuning V_{RF}, the performance of the OOK-DL signal can be sacrificed, but still be error-free, while the amplitude modulation noise is minimized. This sacrifice allows an optimal re-modulation of the optical carrier with the analog OFDM-UL signal.

III. Experiment, Results and Discussion

Fig. 3 demonstrates the experimental setup for transmitting full-duplex OOK-DL and OFDM-UL over 20 km of SSMF. The setup is similar to the one shown in fig. 1 except that we introduce 20km of SSMF and OFDM-UL signal without FEC encoding. The analog signal is based on the IEEE 802.11a WiFi standard and is generated by a programmed Vector Signal Generator (VSG). The frame structure, which is compliant with the standard, contains OFDM symbols for preamble and data payload. The preamble is used for frame synchronization and channel estimation. The payload utilizes all supported modulation modes which are QPSK, 16QAM and 64QAM. The OFDM signal is mixed with 30MHz IF to mimic the down-conversion of WiFi signal from a pass-band (around 2.4GHz or 5.5GHz) into the RSOA's bandwidth of 1.2GHz. The UL signal is acquired by a 10-bit real-time scope working at 100MSa/s, and is processed offline. The signal processing steps are: base-band down-conversion, re-sampling, frame-synchronization, frequency offset removing, preamble-based channel estimation, frequency domain equalization, demodulation, and detection. We measure the error-vector-magnitude (EVM) and BER of the recovered signal. However, the BER is 0 for many cases so only the EVM results are presented here.

EVM values for QPSK, 16QAM and 64QAM of the demodulated OFDM-UL signal and the Q-factor of the OOK-DL signal are depicted in fig. 4. In this case, V_{bias} is fixed at $0.3V_{\pi}$, and V_{RF} is varied from 0.12 to $0.54V_{\pi}$, yielding modulation index from 20 to 90%. The OOK-DL optical power after the MZM is about 5.5dBm and the transmission loss to the RSOA is 11dB. The Q-factor of the OOK-DL signal is above 9.3 dB, and increases linearly proportional to V_{RF}. At $V_{RF} < 0.3V_{\pi}$, the intrinsic system noise is higher than the

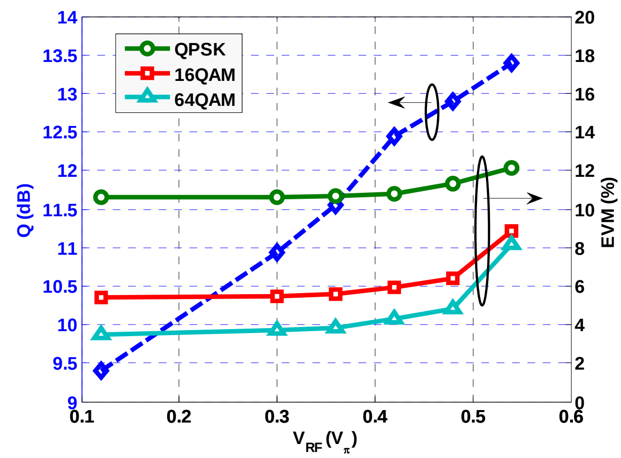

Fig.4. Q-factor of OOK-DL signal and EVM of OFDM-UL signal as a function of V_{RF}.

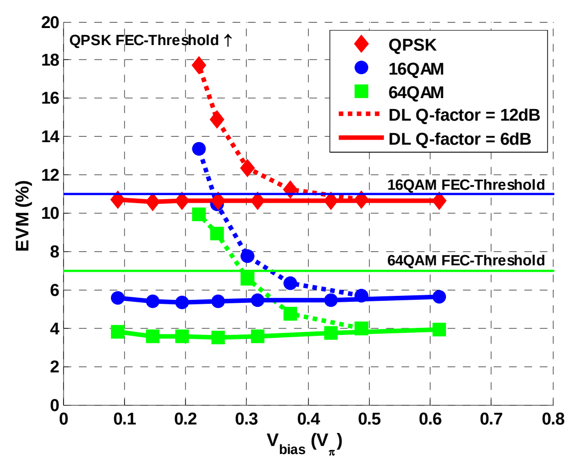

Fig.5. EVM of OFDM-UL signal as a function of V_{bias}

residual DL modulation, making the EVM floors for all modulation modes. This is reasonable since the RTO used for acquiring the UL signal has a nominal 10-bit resolution. As V_{RF} increases above $0.3V_{\pi}$, the EVM values for all modulations increase as predicted from results shown in fig 2.

One can expect that since the Q-factor margin is large, wider operational region or better performance can be achieved if higher V_{bias} and smaller V_{RF} are used to drive the MZM. For this investigation, we define a small V_{bias}, and adjust V_{RF} so that Q-factor of the OOK-DL signal is about 6.3dB. Fixing V_{RF} at that value and changing V_{bias}, we obtain the EVM curves for the UL signal with all modulation formats as shown in fig. 5. All the EVM curves are flat, meaning that the modulation noise from DL signal is below the system noise level. The Q-factor is invariant to V_{bias} as long as the OOK-DL optical power does not saturate the photo-receiver. Changing V_{RF} to obtain a Q-factor of 12dB, the EVM curves start at higher values when V_{bias} is small, and decrease to the floors as V_{bias} reaches $0.60V_{\pi}$. This corresponds to the operating point of the RSOA approaching or getting deeper into the saturation region. At 20km of SSMF, the OFDM-UL signal is below FEC threshold and the OOK-DL signal is error-free.

The OOK-DL and the OFDM-UL performances can be balanced by setting proper values for V_{bias} and V_{RF}. By applying the FEC threshold to each modulation format, the lower boundary of V_{bias} can be derived. Also, by adjusting V_{bias} to reach EVM floors, optimal performance for the UL signal can be obtained. When higher V_{RF} is used to improve the OOK-DL signal, the EVM curve is higher at low V_{bias}, resulting in a smaller region for V_{bias} to maintain OFDM-UL signal below FEC threshold. Combining this result and the one obtained in fig. 4, we develop a good technique to balance the quality for DL and UL signals. It is important that this balancing can be managed at the CO where sophisticated monitoring and controlling are well developed.

IV. CONCLUSIONS

We have studied the modulation erasing in RSOA when input OOK-DL is generated in different conditions. The residual DL modulation can be suppressed efficiently as the bias voltage and RF swing are properly tuned. Therefore, the noise on the reflected optical carrier can be suppressed to allow the transmission of analog OFDM-UL signal. We have implemented an RSOA-based RoF system that transmits full-duplex in-band OOK-DL and OFDM-UL signals over 20km of SSMF. Experimental results show a widely manageable operational region and an insight for selecting proper driving conditions of OOK-DL signal so that reception performances for both DL and UL signals are satisfactory.

REFERENCES

[1] Chang-Hee Lee, W.V. Sorin, Byoung-Yoon Kim, "Fiber to the Home Using a PON Infrastructure," *Lightwave Technology, Journal of*, vol.24, no.12, pp.4568,4583, Dec. 2006.

[2] G. Kardaras, J. Soler, L. Brewka, L. Dittmann, "Fiber to the antenna: A step towards multimode radio architectures for 4G mobile broadband communications," *Advanced Networks and Telecommunication Systems (ANTS), 2010 IEEE 4th International Symposium on*, vol., no., pp.85,87, 16-18 Dec. 2010.

[3] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited]," J. Opt. Netw. 4, 737-758 (2005).

[4] C. Arellano, C. Bock, J. Prat, K-D. Langer, "RSOA-based optical network units for WDM-PON," *Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference. OFC 2006*, vol., no., pp.3 pp.,, 5-10 March 2006.

[5] Wooram Lee, Mahn-Yong Park, Seung-Hyun Cho, Jihyun Lee, Byoung-Whi Kim, Geon Jeong, Byoung Whi Kim, "Bidirectional WDM-PON based on gain-saturated reflective semiconductor optical amplifiers," *Photonics Technology Letters, IEEE*, vol.17, no.11, pp.2460,2462, Nov. 2005.

[6] Y. Xianbin, T. B. Gibbon, I. T. Monroy, "Bidirectional Radio-Over-Fiber System With Phase-Modulation Downlink and RF Oscillator-Free Uplink Using a Reflective SOA," *Photonics Technology Letters, IEEE*, vol.20, no.24, pp.2180,2182, Dec.15, 2008.

[7] Z. A. El-Sahn, J. M. Buset, D. V. Plant, "Overlapped-Subcarrier Multiplexing for WDM Passive Optical Networks: Experimental Verification and Mathematical Analysis," *Lightwave Technology, Journal of*, vol.30, no.5, pp.754,763, Mar. 1, 2012.

[8] A. J. Seeds, "Radio over fibre systems," *IEEE Lasers and Electro-Optics Society, 2008. LEOS 2008. 21st Annual Meeting of the*, vol., no., pp.848,849, 9-13 Nov. 2008.

[9] Y. T. Hsueh, C. Liu; S. H. Fan, J. Yu, G. K. Chang, "A novel full-duplex testbed demonstration of converged all-band 60-GHz radio-over-fiber access architecture," *OFC/NFOEC 2012*, vol., no., pp.1,3, 4-8 March 2012.

[10] H. Pfrommer, M. A. Piqueras, V. Polo, J. Herrera, A. Martinez, J. Marti, "Radio-over-Fiber Architecture for Simultaneous Feeding of 5.5 and 41 GHz WiFi or WiMAX Access Networks," *Microwave Symposium Digest, 2006. IEEE MTT-S International*, vol., no., pp.301,303, 11-16 June 2006.

[11] F. Payoux, F.; Chanclou, P.; Soret, T.; Genay, N.; Brenot, R., "Demonstration of a RSOA-based wavelength remodulation scheme in 1.25 Gbit/s bidirectional hybrid WDM-TDM PON," *Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference. OFC 2006*, vol., no., pp.3 pp.,, 5-10 March 2006.

[12] H. Takesue, T. Sugie, "Wavelength channel data rewrite using saturated SOA modulator for WDM networks with centralized light sources," *Lightwave Technology, Journal of*, vol.21, no.11, pp.2546,2556, Nov. 2003