OFDM Signal Transmission by EPWM Transmitter in Nonlinear RoF Channel

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***Abstract*— Radio-over-Fiber (RoF) technology enables low-loss distribution of RF signals over optical fiber, which contributes much for spreading broadband wireless access services into in-building areas and outdoor dead-spots. However, current broadband wireless access systems employ OFDM schemes and suffer from nonlinear distortion of the RoF channel due to nonlinearity inherent in Electrical to Optical (E/O) conversion. In this paper, a new RoF transmission scheme employing Envelop Pulse-Width Modulation (EPWM) transmitter has been proposed to efficiently suppress the impact of RoF channel nonlinearity on OFDM signals. This idea is executed in a typical RoF channel that uses a Mach-Zehnder modulator as its E/O convertor. It is proved by both simulation and experiment that the EPWM-RoF scheme can achieve linear transmission of OFDM signal via nonlinear RoF channel.**

Keywords-EPWM, OFDM, RoF, nonlinearity, Mach-Zehnder modulator

I. INTRODUCTION

Wireless communications develop towards high data rate to satisfy increasing demands for data communication and Internet access. Orthogonal Frequency Division Multiplexing (OFDM) scheme is widely used in many broadband wireless communication protocols because it has high spectral efficiency while enabling robust signal transmission in multipath fading channels [1]. However OFDM signals are sensitive to nonlinearity, which limits the performance of OFDM system in actual environments. Since OFDM signal has high Peak-to-Average Power Ratio (PAPR), it makes the signal easily suffer from nonlinear distortion that is caused in RF transmitters [2].

The other trend of wireless communication services is extension of coverage area as ubiquitous communications, such as “communication anytime, anywhere, and with anything”. Radio over Fiber (RoF) technology employs optical fiber links which penetrate closer to users to transmit RF signals from a central base station to remote antenna units with low loss [3][4]. Therefore, RoF technology is suitable for wireless access into indoor and outdoor dead spots. However the nonlinearity inherent in optical devices could lead to low performance for the transmission of the OFDM signals. In RoF channels, the nonlinearity that affects the quality of transmitted signals mainly comes from the Electrical/Optical (E/O) converter [3][4].

The Envelop Pulse-Width Modulation (EPWM) transmitter has been proposed for achieving high power efficiency and linear amplification of OFDM signals and its performance has been evaluated for nonlinear RF power amplifiers (PAs) [5]-[8]. By converting input signal envelop to a Pulse-Width-Modulation (PWM) format, EPWM transmitter removes the envelop variation of the input RF signal so that it can protect the input signal against nonlinear distortion. On the other hand, quantization noise is generated during this process, and it can be suppressed by a bandpass filter (BPF) and an Amplitude Noise Compensation (ANC) techniques [7]-[8].

In order to solve the issue of OFDM signal transmission over nonlinear RoF channels, we propose to apply EPWM transmitter for transmitting OFDM signals over the channel. This idea is executed in a typical RoF channel that uses a Mach-Zehnder modulator as its E/O convertor. It is proved by both simulation and experiment that the EPWM-RoF scheme can improve transmission performance of OFDM signal over the nonlinear RoF channel.

II. EPWM - ROF ARCHITECTURE

A. EPWM Transmitter

The architecture of EPWM transmitter is shown in Fig. 1[5, 6]. The input signal is converted into amplitude and phase components by a complex envelop generator. Then the amplitude component $a(t)$ is converted by a $\Delta-\Sigma$ modulator into an PWM envelope signal $e_a(t)$, whereas the phase component $\phi(t)$ undergoes Phase Modulation (PM) of an RF carrier with a carrier frequency of f_c. Resultant EPWM signal $e_{EPWM}(t)$ is the product of the PWM envelop signal and PM signal and has either zero or constant envelop. Therefore a PA can be operated in saturation mode and achieve high power efficiency without affecting the linearity of the input signal.

However, quantization noise is generated in the $\Delta-\Sigma$ modulator and it degrades signal quality and causes outband radiation for the transmitted signal. In order to reduce the effects, the input signal should be oversampled with a higher order ratio so that the quantization noise can be sufficiently suppressed by noise shaping property of the $\Delta-\Sigma$ modulator [9]. Also, a narrow-band BPF is necessary to remove quantization noise that radiates outside signal spectrum. It has relatively high insertion loss, which decreases the power efficiency of the transmitter.

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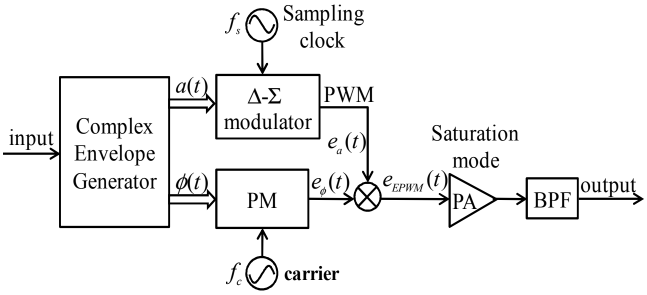


Figure 1. EPWM transmitter

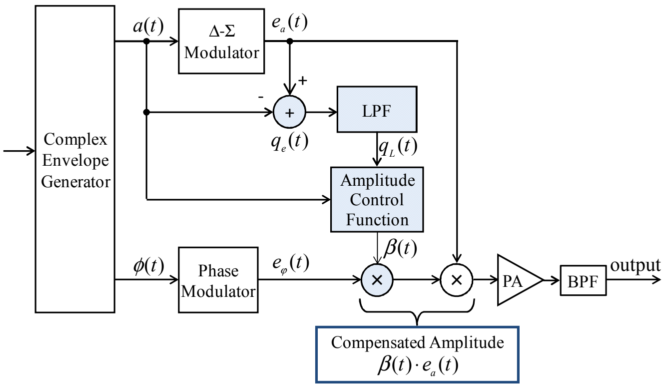


Figure 2. ANC-EPWM transmitter

Principle of the Amplitude Noise Compensation EPWM (ANC-EPWM) transmitter is shown in Fig. 2 [7]-[8]. In this method, the quantization noise close to the signal spectrum is significantly suppressed by controlling the amplitude of the phase modulator output with a compensation coefficient $\beta(t)$ that is given by

$$\beta(t)=\frac{a(t)}{a(t)+q_L(t)}=\frac{a(t)}{a(t)+h_{LPF}(t)*q_e(t)} \tag{1}$$

Where $q_L(t)$ is the output signal of the LPF, $q_e(t)$ is the quantization noise generated by the Δ-Σ modulator, $h_{LPF}(t)$ is the impulse response of the LPF and * denotes convolution operation. Then ANC-EPWM signal is expressed as

$$e_{ANC-EPWM}(t)=\beta(t)\cdot e_a(t)\cdot e_\phi(t) \tag{2}$$

By multiplying $\beta(t)$, the quantization noise close to the signal spectrum is significantly suppressed. Thus ANC-EPWM transmitter can relax the narrow bandwidth requirement for the BPF. Since $q_L(t)$ in Eq. (1) is smaller than $a(t)$, compensation coefficient $\beta(t)$ has narrow range of distribution around 1. Thus, resultant ANC-EPWM signal shows small amplitude variation and still keeps favorable characteristic of EPWM signal for nonlinear transmission.

In order to avoid input signal overloading of the $\Delta-\Sigma$ modulator, clipping level control is necessary for OFDM signals that have high peak to average power ratio (PAPR). The control is performed by using a clipping ratio of $E_{\max}/\sigma$ [6], where $E_{\max}$ is the step-size of $\Delta-\Sigma$ modulator and σ is the normalized amplitude corresponding to the average power of the OFDM signal.

B. EPWM-RoF Transmission

The proposed EPWM-RoF transmission system is shown in Fig. 3. An EPWM or ANC-EPWM format signal with an RF frequency of f_c is generated by the EPWM transmitter and then it is fed to the E/O convertor for intensity-modulation of the light source. After transmitted through the optical fiber, the optical signal is reconverted into electric signal by a photo detector (PD) as an O/E convertor.

The RF signal is recovered as its original OFDM signal by filtering the PD output signal with a BPF of the center frequency f_c. Since the EPWM transmitter suppress the amplitude variation of the input RF signal, impact of the nonlinearity in the RoF channel can be reduced to the minimum. Both EPWM and ANC-EPWM transmitters can be used for RoF transmission.

III. Nonlinear RoF Transmission Analysis

A. Nonlinearity of Mach-Zehnder Modulator

We consider typical RoF channel using a Mach-Zehnder (MZ) modulator as shown in Fig. 4. Suppose that the light source signal is given as $V_{in}=A_{opt}\cos(\omega_{opt}t)$, the output optical signal from the MZ modulator is expressed by

$$V_{MZ}=A_{opt}\cos\left(\frac{\pi}{2V_\pi}\left(V_{RF}(t)+V_{bias}\right)\right)\cos(\omega_{opt}t) \tag{3}$$

where A_{opt} and ω_{opt} are the amplitude and angular frequency of input light source, respectively [10]. $V_{RF}(t)$ is an input RF signal and V_{bias} is the input DC bias voltage that is optimized for the MZ modulation characteristic.

Fig. 5 shows an input/output characteristic of the MZ modulator that is fit to an actual device. The extinction voltage V_π is the half cycle voltage, and the DC bias is used to

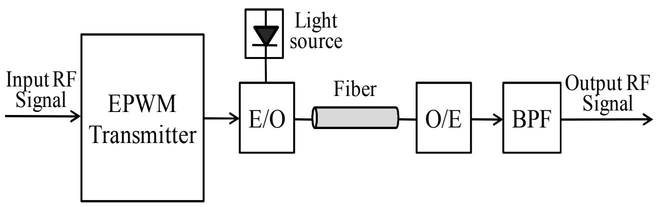


Figure 3. EPWM-RoF transmission system

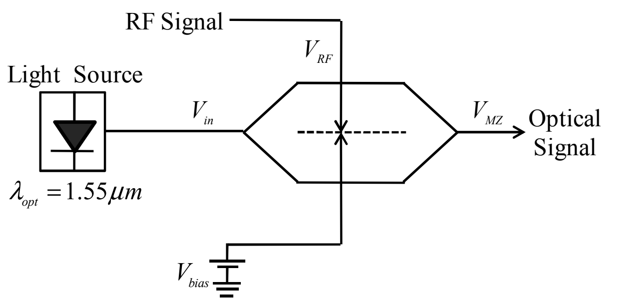


Figure 4. Mach-Zehnder Modulator

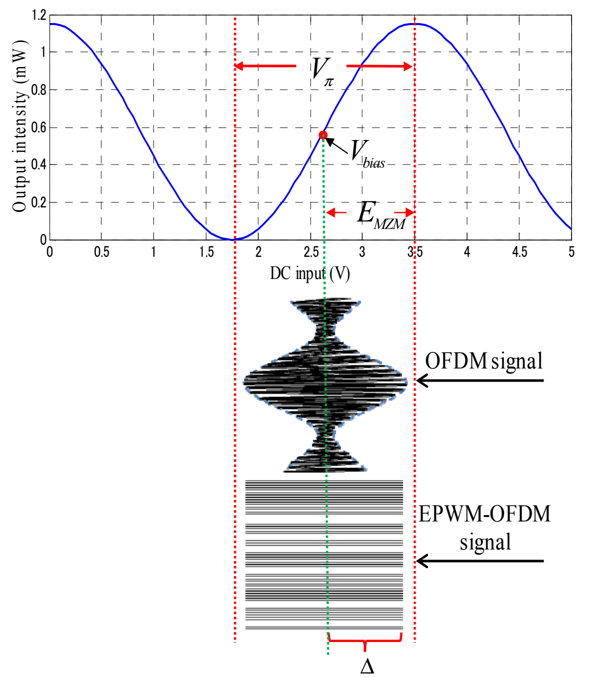


Figure 5. Input/output characteristic of MZ modulator and two input signals.

control the modulator's operating point so that we can choose the best linear transmission region of the modulator.

B. *Output Spectra Analysis for MZ Modulator*

1) *General Mathematical Analysis*

The input RF signal can be expressed as follows

$$V_{RF}(t) = A_{RF}(t)\cos\left(\omega_c t + \phi(t)\right) = A_{RF}(t)\cos\left(\Phi(t)\right) \qquad (4)$$

where $\Phi(t) = \omega_c t + \phi(t)$, and ω_c is the carrier angular frequency of the RF signal. Using the trigonometric formula and Bessel function, we derive the MZ modulator output from equation (3):

$$\begin{aligned}
V_{MZ}(t) &= A_{opt}\cos\left(\frac{\pi\left[V_{RF}(t)+V_{bias}\right]}{2V_\pi}\right)\cos(\omega_{opt}t)\\
&= A_{opt}\cos a\Big\{J_0(m)\cos(\omega_{opt}t)\\
&\quad+\sum_{n=1}^{\infty}\Big[J_{2n}(m)\cos\left(\omega_{opt}t+2n\Phi(t)-n\pi\right)\\
&\quad+J_{2n}(m)\cos\left(\omega_{opt}t-2n\Phi(t)+n\pi\right)\Big]\Big\}\\
&\quad+A_{opt}\sin a\Big\{\sum_{n=1}^{\infty}\Big[J_{2n-1}(m)\cos\left(\omega_{opt}t+(2n-1)\Phi(t)-n\pi\right)\\
&\quad+J_{2n-1}(m)\cos\left(\omega_{opt}t-(2n-1)\Phi(t)+n\pi\right)\Big]\Big\}
\end{aligned} \qquad (5)$$

where $K = \pi/2V_\pi$, $a = KV_{bias}$ and $m = KA_{RF}(t)$.

As shown in (5), spectra of the MZ modulator output signals consist of even harmonic waves and odd harmonic waves. The relationship between the output amplitude and the input amplitude of each harmonic wave is the Bessel function of the first kind. From the derived MZ modulator transmission function we can see that the signal component useful for us is the odd harmonic wave with $n = 1$. That is,

$$\begin{aligned}
V_{out}(t) &= A_{opt}\sin a\Big\{\sum_{n=1}^{\infty}\Big[J_{2n-1}(m)\cos\left(\omega_{opt}t+(2n-1)\Phi(t)-n\pi\right)\\
&\quad+J_{2n-1}(m)\cos\left(\omega_{opt}t-(2n-1)\Phi(t)+n\pi\right)\Big]\Big\}\Big|_{n=1}\\
&= A_{opt}\sin a\cdot J_1(m)\Big[\cos\left(\omega_{opt}t+\Phi(t)\right)+\cos\left(\omega_{opt}t-\Phi(t)\right)\Big]
\end{aligned} \qquad (6)$$

After O/E conversion, $V_{out}(t)$ is demodulated to the RF signal.

2) *Simulated Results for OFDM Input Signal*

In order to obtain nonlinear output of an OFDM signals having continuous spectrum, we conduct MZ modulator simulation by using MATLAB. We employed the IEEE 802.11a OFDM signal in this simulation. As shown in Fig. 6, there are two branches having the same RF carrier frequency f_c . One of the branches is used to transmit the OFDM signal over the RoF channel, in the other branch the same signal is converted to ANC-EPWM format at first, then the resultant ANC-EPWM signal is transmitted over the RoF channel. The spectra of optical OFDM-RoF signal and ANC-EPWM-RoF signal from MZ modulator are obtained and compared.

Simulation conditions are listed in Table. 1. Oversampling ratio is defined as the ratio of oversampling frequency to basic sampling frequency. Clipping probability determines the clipping level of $\Delta-\Sigma$ modulator for an input signal [6]. To identify the MZ modulator transmission function and make the simulation results fit to actual situation, we conducted an experiment to measure the characteristic of MZ modulator.

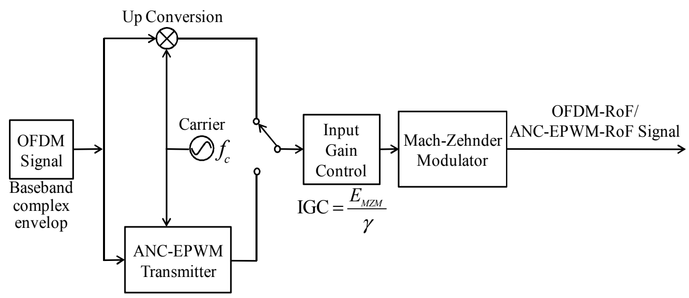
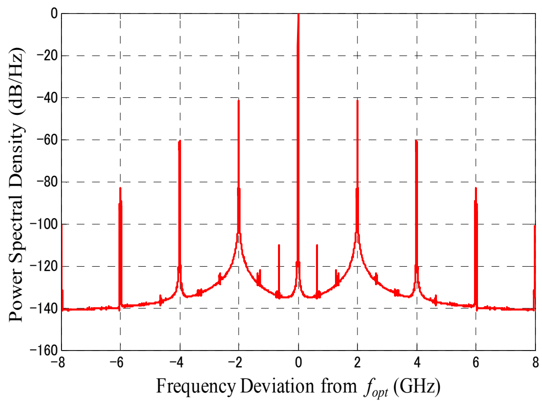


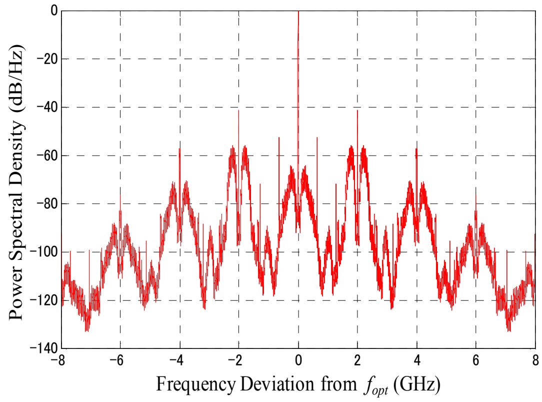
Figure 6. Simulation diagram

TABLE I. SIMULATION CONDITIONS

OFDM Signal	IEEE 802.11a, $f_c = 2\text{GHz}$
ANC-EPWM Transmitter	2nd-order $\Delta-\Sigma$ modulator, with null frequency $f_0 = 60\text{MHz}$, Oversampling Ratio of 32, Clipping Probability of 0.1%
MZ Modulator	$V_\pi = 1.75\text{V}$, $V_{bias} = 2.625\text{V}$
Input Gain Control	$\gamma = 2.7$

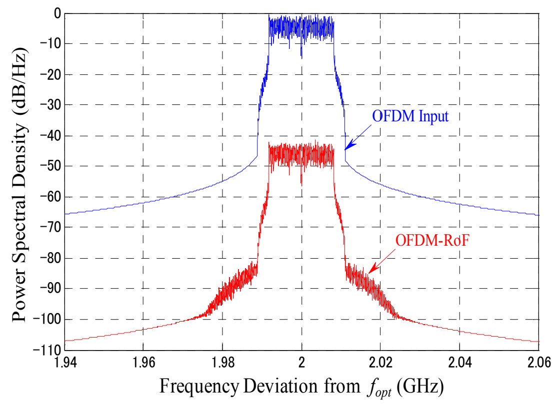


(a) OFDM-RoF signal

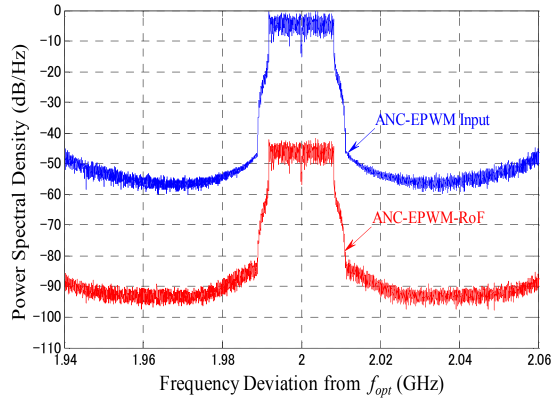


(b) ANC-EPWM-RoF signal

Figure 7. Simulated optical signal spectra



(a) OFDM-RoF signal



(b) ANC-EPWM-RoF signal

Figure 8. Optical signal spectra around freuqency deviation of 2GHz

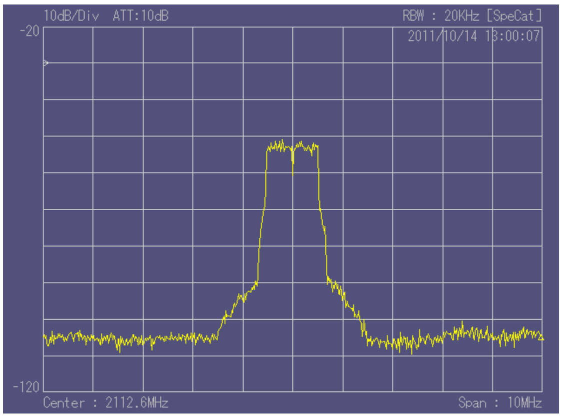
The result is very close to the equation model in (3). Measured extinction voltage of MZ modulator is 1.75V. Factor γ which is used to adjust the value of input gain control defined by $IGC = E_{MZM}/\gamma$ is set to be 2.7, where $E_{MZM} = V_\pi/2$ as shown in Fig. 5.

Fig. 7 shows the optical power spectral density (PSD) of the OFDM-RoF signal (a) and ANC-EPWM-RoF signal (b), both output from MZ modulator. As the general mathematical analysis describes, there are even harmonic waves and odd harmonic waves in the optical output spectra. The desired signal component expressed by Eq. (6) appears at the frequency derivation of $\pm$2GHz. The other components with different frequency deviations are nonlinear components. In Fig. 7(b), quantization noise spectrum is superposed to the OFDM signal spectrum. They can be removed by BPF at the center frequency of 2GHz after demodulating the optical signal.

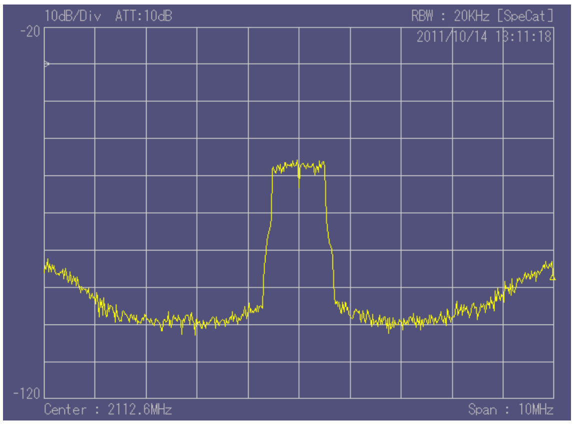
The PSD of RF signals at 2GHz can be obtained by zooming at the spectrum at 2GHz away from the optical center frequency in Fig. 7. They are shown in Fig. 8. Figure 8(a) gives the PSD of input OFDM signal and optical output OFDM-RoF signal when $\gamma = 2.7$. Figure 8(b) shows the PSD of input ANC-EPWM signal and optical output ANC-EPWM-RoF signal with the same γ. As shown in the figures, inter-modulation distortion happens in OFDM-RoF signal, while distortion in ANC-EPWM-RoF signal is negligible.

IV. RoF Experiment

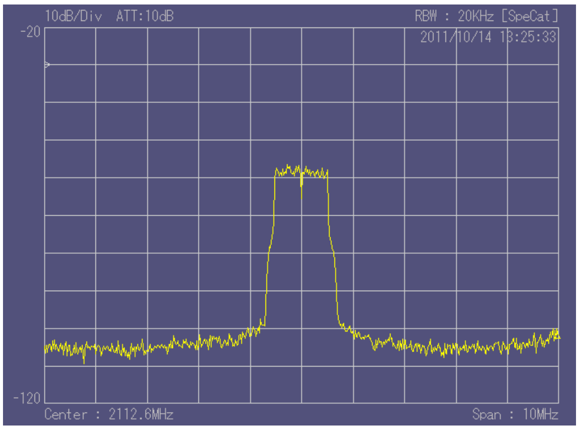
The experimental setup is the same as the EPWM-RoF transmission system in Fig. 3. Signal parameters are similar as listed in Table. 1. We generated the IEEE 802.11a OFDM signal and ANC-EPWM signal at first in baseband, then upconverted them to 2.1126GHz using a vector signal generator (E4438C). Due to the limitation of the maximum sampling frequency of vector signal generator, the time scale of the baseband signals are multiplied by 16. Therefore frequency span is compressed by 1/16. DC bias voltage was added to the RF signals to choose linear working region of the E/O convertor. T.MZH1.5-10PD-ADC-S-Y-Z MZ modulator having the same input/output characteristic in Fig. 5 was employed as the E/O convertor. The optical signals were reconverted to electric signal by a PD of type DSC50S. Then we used a BPF having the bandwidth of 3.84 MHz to remove quantization noise in ANC-EPWM signal and recover the original OFDM signal.



(a) OFDM-RoF output signal



(b) ANC-EPWM-RoF output signal without BPF



(c) ANC-EPWM-RoF output signal with BPF

Figure 9. Measured RF signal spectra from PD

Fig. 9 shows the RoF transmission experiment results. Fig. 9(a) gives the output spectrum of OFDM-RoF signal from the PD. From the Fig. 9(a) we can see the intermodulation distortion is very close to the simulation result shown in Fig. 8 (a) and cannot be removed by the BPF after the PD. Fig. 9(b) shows the output spectrum of ANC-EPWM-RoF signal from the PD without BPF. It is close to the simulation result shown in Fig. 8 (b). From Fig. 9(c) we can see that after filtering by the BPF, quantization noise in ANC-EPWM signal is removed and the original OFDM signal is recovered with minimum distortion. Comparing intermodulation distortion levels in Fig 9(a) and 9(c), superposed in the signal spectrum, the ANC-EPWM-RoF transmission causes less damage for the OFDM signal. Adjacent channel leakage power ratio (ACLR) for the signals shown in figure 9(a) and figure 9(c) are -41.2dB and -43.3dB, respectively. 2.1dB improvement is achieved by employing ANC-EPWM signal.

V. CONCLUSIONS

In this paper, we propose to apply EPWM transmitter for OFDM signal transmission in nonlinear RoF channel. Both simulation and experiment were conducted to verify the performance of EPWM-RoF transmission. The experimental results well coincide with the simulated results, and sufficiently support our idea that EPWM transmitter has very good performance in dealing with nonlinearity of optical modulator which is the major factor lead to the nonlinearity of RoF channel.

In our future work, Error Vector Magnitude (EVM) performance of EPWM-RoF transmission system will be evaluated. We will also verify EPWM-RoF feasibility and performance using direct-modulation Laser Diode (LD) instead of MZ modulator.

ACKNOWLEDGMENT

This work was supported by KAKENHI (23360169).

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