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Predistortion for Frequency-Dependent Nonlinearity of a Laser in RoF Systems

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Abstract

In radio-over-fiber (RoF) systems, nonlinear compensation is essential to improve performance. Among the several existing nonlinear compensation techniques, we investigate a predistortion technique for a directly modulated laser in an RoF system. First, we obtain the input-to-output response of a directly modulated laser at 160, 820, and 1,540 MHz. The results show that the laser response is dependent on the frequency band. Second, we design an optimal predistortion circuit to compensate for the nonlinear responses of three frequency bands. We design the predistortion circuit with two options: each predistortion circuit for each frequency band and one single predistortion circuit for all the three frequency bands. Finally, we present the simulation results of the predistortion system obtained using a commercial simulator. These results show that the third intermodulation distortion (IMD3) is improved by 0.6–9 dB for the three frequency bands with only a single predistortion circuit.

Index Terms: Intermodulation, Nonlinearity, Predistortion, Radio over fiber

I. INTRODUCTION

In the current mobile networks such as long-term evolution advanced (LTE-Advanced) networks, base station networks composed of a central digital unit (DU) and remote radio units (RUs) are widely used because of several advantages such as deployment flexibility and low installation cost [1]. In these base station networks, Common Public Radio Interface (CPRI) [2] or Open Base Station Architecture Initiative (OBSAI) [3] is currently used as the link standard between DU and RU. In these link standards, analog radio signals are sampled, quantized, and then transmitted through digital optical fiber communication. This method was sufficient to support a couple of LTE radio channels. However, future mobile networks above LTE-Advanced will have wider channel bandwidths and each RU

will need to support more than 8×8 multiple-input multiple-output (MIMO) schemes [4]. To support such future mobile networks, a huge CPRI or OBSAI interface is required. For example, to support an RU composed of three sectors with four 20-MHz channels and 8×8 MIMO, a CPRI channel of about 120-Gb/s is required. Moreover, in a real mobile network, a DU needs to support several RUs.

To support the increased link capacity between DU and RU more economically, the radio-over-fiber (RoF) technology has been proposed [5-8]. In RoF systems, several analog radio signals are multiplexed by using frequency division multiplexing (FDM) and transmitted as an analog optical transmission. Although the RoF technique can reduce the required bandwidth dramatically, its signal quality can be degraded easily by the nonlinearity in the RoF transmission. Such nonlinearity usually limits the performance of RoF

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systems and makes it difficult to meet the error vector magnitude (EVM) requirement of the LTE-Advanced standard [9].

Therefore, there has been considerable effort to reduce the nonlinearity in RoF systems. Among the existing approaches, the predistortion technique can be a cost-effective solution to reduce the nonlinearity in RoF systems that use directly modulated lasers.

In this letter, we investigate the nonlinear characteristics of a directly modulated laser. It will be shown that the response of a directly modulated laser is dependent on the frequency. Further, such frequency-dependent nonlinearity can be compensated for by using only a single predistortion circuit based on the third-order predistortion. Finally, the third intermodulation distortion (IMD3) improvement by the proposed predistortion will be shown.

II. LASER CHARACTERISTICS AND PREDISTORTION IMPLEMENTATION

The first step for the realization of the predistortion technique is an experimental analysis of a directly modulated laser. Then, a predistorter block is designed by using the obtained laser response.

A. Nonlinear Characteristics of a Laser

To obtain the nonlinear characteristics of a laser, an experimental setup comprising of a laser diode (Teradian LD TAD5204-ESSN), a variable optical amplifier, and a photodiode (Emcore PD FOL-13TR1/S5-55-SA) was implemented. Fig. 1 shows this experimental setup. The laser response was obtained at three frequencies: 160, 820, and 1,540 MHz. To get them, the output power was measured by changing the input power from 3 to 18 dBm. Fig. 2 shows the measured laser responses at the three frequencies. The results show that the laser response is frequency-dependent. However, we will show that it is possible to compensate for the different nonlinearities with only one predistorter in a later part of this paper.

B. Design of Predistortion

The predistortion is implemented using the inverse function of the nonlinear response. Fig. 3 shows graphically the main idea of the predistortion compensation. There are several approaches to obtain the inverse function of a nonlinear system [10-13]. In this study, we obtained the inverse of the laser response by changing the input and the output (i.e., changing $y \rightarrow x'$ and $x \rightarrow y'$, where (x, y) is the input and output of the laser response and (x', y') is the inverse of the laser response). The obtained inverse function
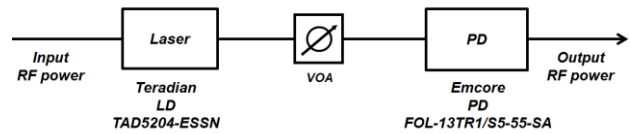

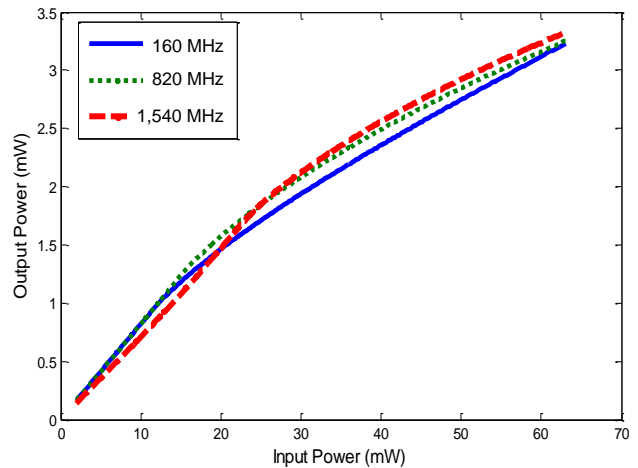**Fig. 1.** Experimental setup for detecting the nonlinear characteristic of a laser.

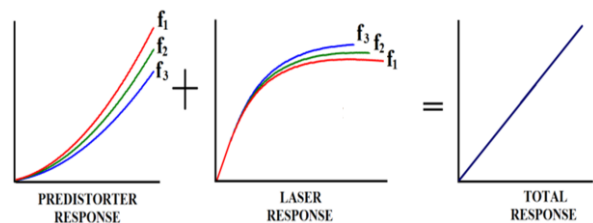**Fig. 2.** Laser responses at three frequencies.

Fig. 3. Principle of predistortion.

is modeled with a third-order polynomial function, which is the predistortion block.

C. Predistortion for Each Frequency Band

As the first option, we consider making three respective predistortion blocks for each frequency band. Because the laser responses of the three frequency bands are different, the best option would be to create three respective predistortions for each frequency band. Each predistortion is mathematically represented by a polynomial, Eq. (1) Usually, to compensate the nonlinearities in a system, the inverse function of the amplitude response (voltage or current) is used. However, as the power is the voltage square divided by the resistance ($P = V^2/R$), the inverse function of the power is used in this study.
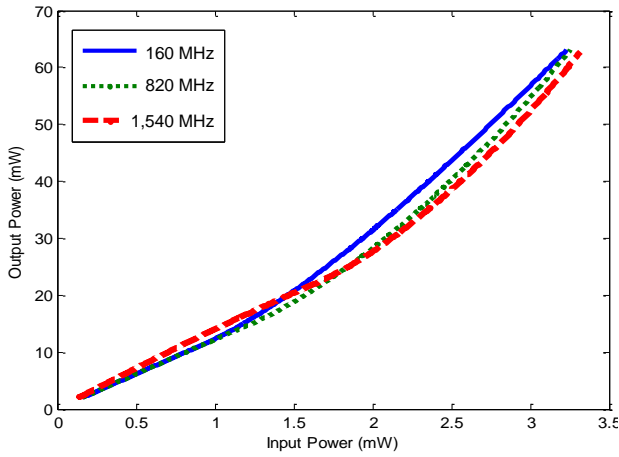
Fig. 4. Predistorter response.

Table 1. Coefficients of the predistortion for each frequency

Freq. (MHz)	a_3	a_2	a_1
160	26.997	20.662	10.385
820	107.330	−12.203	12.269
1,540	144.620	−38.960	16.067

$$y = a_3 x^3 + a_2 x^2 + a_1 x, \tag{1}$$

where a_3, a_2, and a_1 are the coefficients. The values of the coefficients for three different predistortions are shown in Table 1. The three predistortion functions are shown in Fig. 4.

D. Predistortion for Each Frequency Band

As the second option, the previous three predistorters for each frequency band are replaced by a single predistorter that compensates for the nonlinearity in all the three bands (160, 820, and 1,540 MHz). To design the single predistorter, we calculate the average nonlinearity of the three frequencies and then, obtain its inverse function. This inverse function is the predistorter. The coefficients of the single predistorter are presented in Table 2. There are two cases in Table 2. Case 1 is the original predistorter, and Case 2 is a simpler predistorter that does not have the second-order term.

Table 2. Coefficients of the predistortion for all the frequency bands

	a_3	a_2	a_1
Case 1	86.929	−8.3223	12.798
Case 2	67.385	0	12.026

III. RESULTS AND DISCUSSION

The simulations are conducted with two options, as shown in Fig. 5. In the first option, a respective predistorter is used for each frequency band. Therefore, three predistorters are used in the first option. In the second option, a single predistorter is used for all the three frequency bands. Tables 1 and 2 show the mathematical models of the predistorter. Fig. 5 shows the block diagram of the predistorter circuit. The predistorter circuit is composed of mixers, linear amplifiers, and negative converters. The simulation is carried out with a commercial simulator "AWR Design Environment."

The performance of the nonlinear compensator is measured through the two-tone IMD3. IMD3 is the difference between the power of the fundamental signal and the third-order harmonics, measured at the system output. The two-tone used for the measurement consists of the three main frequencies (160, 820, and 1,540 MHz) and the main frequencies +60 MHz.

The simulation results for the first option are shown in Fig. 6. The IMD3 is shown on the vertical axis, while the predistorter input power is plotted on the horizontal axis. This input power is the same as the power shown in Fig. 4. Further, the output power of the predistorter is the same as the power shown in Fig. 2. The IMD3 is measured at 160, 820, and 1,540 MHz with and without the predistorter. The results show that the predistorter of the first option (different predistorter for each frequency band) improves the IMD3 by 0–15 dB and 0.5–4.3 dB at 160 and 820 MHz, respectively. In contrast, at 1,540 MHz, the IMD3 is degraded by 0–2 dB in the low-power region, while there is a slight compensation in the high-power region.
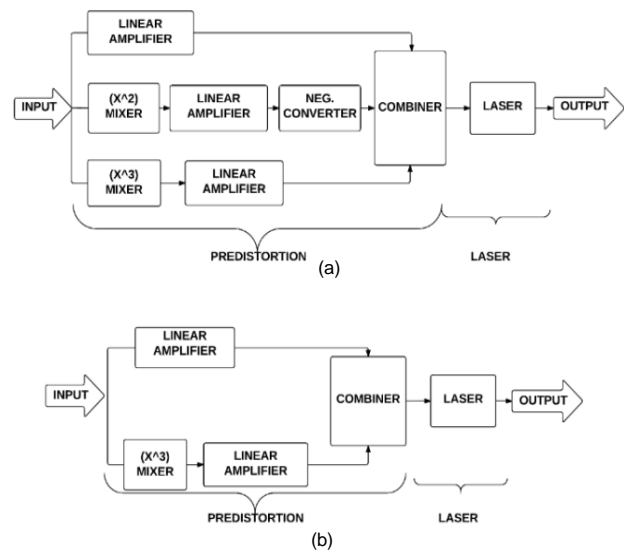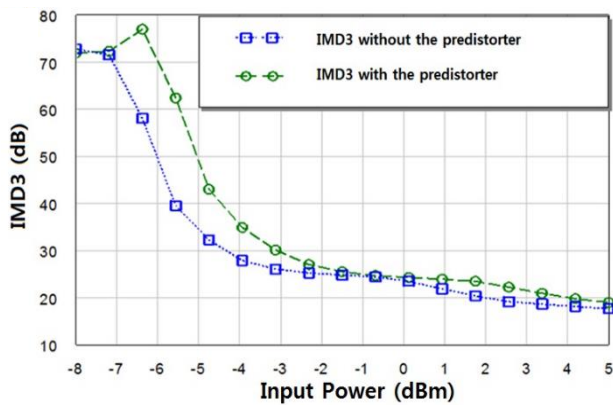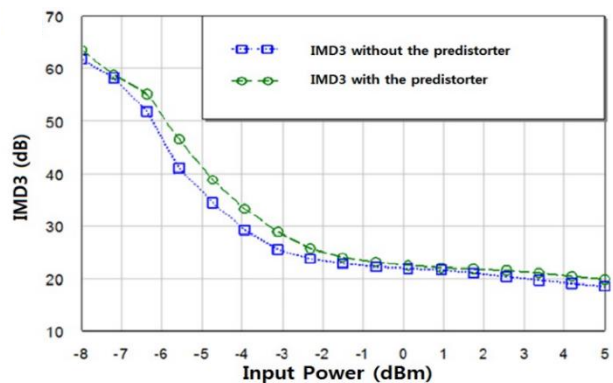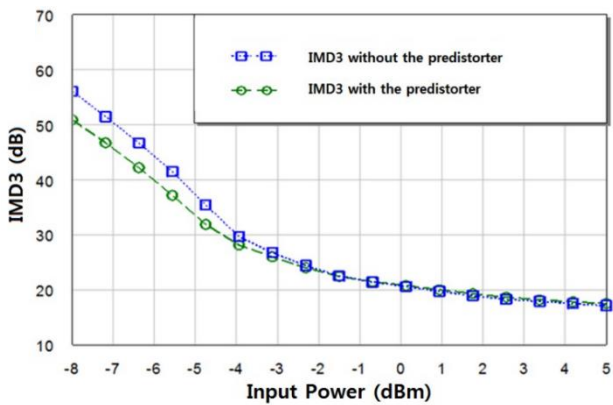

Fig. 5. Block diagram of the predistorter circuit in (a) case 1 (original version) and (b) case 2 (simpler version).
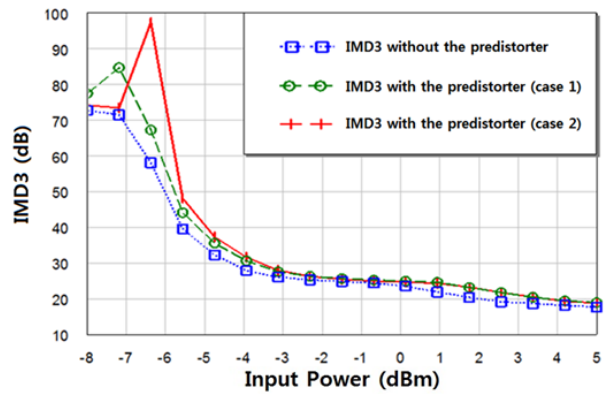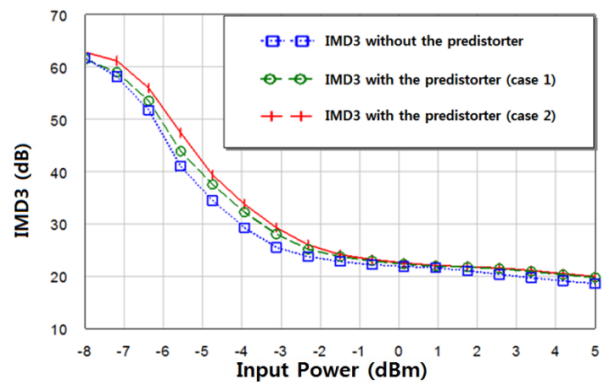
Fig. 6. IMD3 of the system with and without a respective predistorter in the frequency band of (a) 160 MHz, (b) 820 MHz, and (c) 1,540 MHz.

Fig. 7. IMD3 of the system with and without a single predistorter in the frequency band of (a) 160 MHz, (b) 820 MHz, and (c) 1,540 MHz.
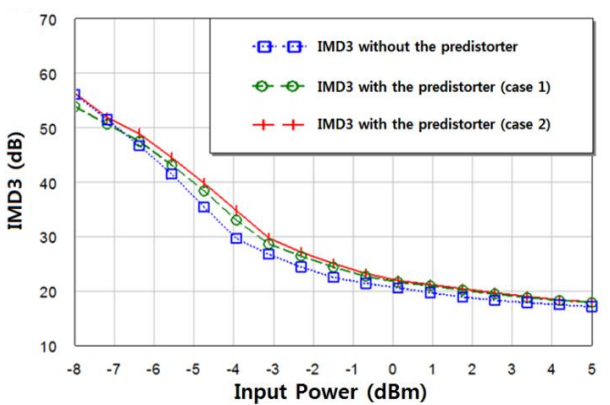
As the second option, only a single predistorter is used for all the three frequency bands. However, this single predistorter has two cases, as shown in Table 2. The performances of these two predistorters are compared using the IMD3 parameter. Fig. 7 shows the IMD3 results of the system with and without the predistorter. The IMD3 improvements obtained using the single predistortion are summarized in Table 3. These results show that only a single predistorter can improve the IMD3 performance by 0–9 dB.

Table 3. IMD3 Improvements with the predistortion (unit: dB)

	160-MHz band	820-MHz band	1,540-MHz band
Case 1	0.7–8.2	0–4.2	0–3.8
Case 2	0.8–9	0.6–6	1.3–5.5

IV. CONCLUSION

In this study, we evaluated the performance of a predistortion technique in a directly modulated laser for an RoF system. First, we showed that the nonlinear characteristics of a laser are dependent on the frequency band. Therefore, we considered two cases for the predistorter system: a respective predistorter per frequency band and a single predistorter for all the frequency bands. Our results revealed that case 1 can compensate for the nonlinear characteristics at the low-frequency bands (160 and 820 MHz). However, at 1,540 MHz, the compensation performance is poor or even degrades the system linearity. However, case 2 revealed better linearization features. The simulation results showed that the single predistorter improved the IMD3 by 0–9 dB in all the bands. This improvement was similar to that of other predistorters that are based on each frequency band.

ACKNOWLEDGMENTS

REFERENCES

[1] S. M. Kim, "Limits of digital unit-remote radio unit distance and cell coverage induced by time division duplex profile in mobile WiMAX systems," *International Journal of Communication Systems*, vol. 26, no. 2, pp. 250-258, 2013.

[2] Common Public Radio Interface (CPRI) [Internet]. Available: http://www.cpri.info.

[3] Open Base Station Architecture Initiative (OBSAI) [Internet]. Available: http://www.obsai.com.

[4] K. T. Truong and R. W. Heath, "Effects of channel aging in massive MIMO systems," *Journal of Communications and Networks*, vol. 15, no. 4, pp. 338-351, 2013.

[5] M. Morant, J. Prat, and R. Llorente, "Radio-over-fiber optical polarization-multiplexed networks for 3GPP wireless carrier-aggregated MIMO provision," *Journal of Lightwave Technology*, vol. 32, no. 20, pp. 3721-3727, 2014.

[6] M. Sauer, A. Kobyakov, and J. George, "Radio over fiber for picocellular network architectures," *Journal of Lightwave Technology*, vol. 25, no. 11, pp. 3301-3320, 2007.

[7] K. S. Kim, J. H. Lee, and J. C. Jeong, "Generalized analysis on the combined effect of SPM and fiber chromatic dispersion on subcarrier multiplexed optical transmission systems for RoF applications," *Journal of the Optical Society of Korea*, vol. 15, no. 2, pp. 132-139, 2011.

[8] S. H. Cho, H. Park, H. S. Chung, K. H. Doo, S. S. Lee, and J. H. Lee, "Cost-effective next generation mobile fronthaul architecture with multi-IF carrier transmission scheme," in *Proceeding of Optical Fiber Communication Conference*, San Francisco, CA, 2014.

[9] 3GPP TS 36.104, Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception, V12.0.0, 2013.

[10] R. Sadhwani and B. Jalali, "Adaptive CMOS predistortion linearizer for fiber-optic links," *Journal of Lightwave Technology*, vol. 21, no. 12, pp. 3180-3193, 2003.

[11] H. Matsubara, K. Ishihara, N. Miyadai, and T. Nojima, "Hybrid predistortion to compensate third-and fifth-order intermodulation of a 2 GHz power amplifier using cuber predistortion and second harmonics injection," *IET Microwaves, Antennas & Propagation*, vol. 2, no. 8, pp. 813-822, 2008.

[12] X. Tian, Z. Wang, and W. Li, "Realization of an analog predistortion circuit for RF optical fiber links," *Journal of Semiconductors*, vol. 30, no. 11, article no. 115005, 2009.

[13] C. B. Haskins, "Diode predistortion linearization for power amplifier RFICs in digital radios," Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2000.

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