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Intermodulation Distortion Cancellation by Feedforward Linearization of Power Amplifier

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ABSTRACT
Intermodulation distortion has been a major source of linearity when a power amplifier is used for multichannel systems in wireless communication. Since, distortion products appear close to original input carriers they need to be cancelled out so that information reaches unaltered and distortion-less at the destination. In this paper, feedforward technique has been selected to obtain maximum intermodulation distortion reduction. To demonstrate linearity improvement, along with IMD measurement, carrier to IMD power ratio (C/I) and intercept points are also evaluated. Later on, the feedforward power amplifier is tested by sweeping input power within a specified range and graphs for IMD and intercept points are derived. The results show that the feedforward linearized power amplifier achieves best results when operated at input power levels around and above -12 dBm.
Keywords: Carrier to IMD power ratio (C/I), Feedforward (FF), Intercept point (IP), Intermodulation distortion (IMD), Linearization, Nonlinearity, Power amplifier (PA).

I. INTRODUCTION

The biggest milestone in the path of power amplifier's linearity is the intermodulation distortion which is generated in power amplifier's output when a multi-carrier signal is applied as an input. Alongside gain compression, harmonic distortion and adjacent channel interference [1]; it is very important to keep a check on the intermodulation distortion levels also to ensure a distortion-less and linear output. The intermodulation distortion products are basically the additional tones generated from multi-carrier amplification appearing in the vicinity of the original transmitted carriers [2]. These extra undesired frequencies may pose a threat of adjacent channel interference [3]. Intermodulation distortion of third-order, fifth-order or seventh-order is generally characterized by their corresponding intercept point (IP) [4]. Since, third-order intermodulation distortion appears closest to the original carriers; the third-order intercept point is of much greater concern. The greater the third-order intercept point better is the linearity and lower is the third-order intermodulation distortion [5].

The linearization process aims to modify the amplifier output in such a way that only linearized and undistorted signal is achieved at the final output of linearization stage. Several linearization methods are available today to provide the necessary distortion cancellation. The most popular include predistortion, feedforward and feedback [6]. Feedforward technique having decent potential of managing the multi-carrier signal [7], presenting wide bandwidth and good cancellation of IMD [8] is preferred.

Feedforward works on the principle of suppressing the amplifier's output to input level, subtracting the resulting signal from input itself giving only distortion, then amplifying the distortion and finally subtracting the amplified distortion from amplified input resulting in linearized output [9]. The traditional feedforward topology was used to linearize a third-generation PA in [10] but due to 180º phase difference of upper and lower distortion products the upper and lower IMD levels were unevenly cancelled. Whereas in [7] using the common feedforward method and proper setting of delays in both loops, somewhat close and even IMD cancellation was achieved. In [11] an improved over-compensation FF method was presented and in [12] the feedforward technique was upgraded with another distortion cancellation loop to provide further improved linearity. But these two improved circuits are rather much more complex and increase the cost of implementation for a small additional IMD cancellation where much more IMD reduction can be achieved by proper setting of amplitude and phase shifters along with careful selection of error amplifier.

In this paper, the vintage feedforward topology is implemented to linearize a 16W WCDMA power amplifier [13] used for repeater applications in frequency range of 2110-2170 MHz. To demonstrate the effectiveness of this approach intermodulation distortion levels are measured upto seventh order and compared with those from a non-linearized PA. The distance between original carriers and IMD products is measured and the intercept points (IP) are computed. The paper is organized as follows: section II describes how the intermodulation distortion is generated by taking a multicarrier signal as an example, section III describes the basic working of feedforward technique, section IV describes the simulation and results and section V gives the conclusion.

II. INTERMODULATION DISTORTION

A power amplifier when subjected to a two-tone signal generates intermodulation products in the output resulting in nonlinearity. It must be noted that not all the harmonics in the output of amplifier are problematic. Let us see how these harmonics are generated at the amplifier's output.
Let be the signal given as input to power amplifier. Then the output of amplifier expressed by expanding the power series [14] will be:

(1)

Let input signal consists of two carriers of dissimilar frequencies, i.e., the signal is a two tone signal given by,

(2)

where, $\omega_1 \neq \omega_2$. The first term of (1) gives fundamental tones at the frequencies of ω_1 and ω_2 as shown below:

(3)

The second term of output in (1) can be expanded mathematically as,

(4)

The first and last term of (4) are straightforward and gives harmonics at the frequencies of $2\omega_1$ and $2\omega_2$. But the second term is rather complex and needs to be simplified as shown below:

(5)

Using trigonometric identity: in (5) we get,

(6)

So, as seen in (6), we get two second-order products at the frequencies of $(\omega_1 + \omega_2)$ and $(\omega_1 - \omega_2)$ respectively. These signals do not pose much problem because they merely come outside the amplifier bandwidth as shown in Fig. 1.

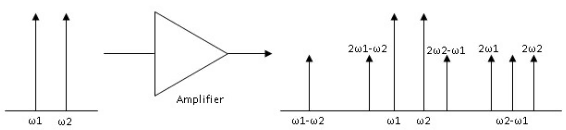

Fig. 1 Power Amplifier Output

Now, the third term of amplifier output is given by,

(7)

Here also, the first and last term are the harmonics at the frequencies of $3\omega_1$ and $3\omega_2$. Whereas, the second and third terms need to be solved mathematically as shown below:

(8)

Using trigonometric formulae: & in (8) we get,

(9)

Similarly,

(10)

Therefore, as observed from (9) and (10), the second and third terms of (7) result in four additional signals at the frequencies of $(2\omega_1 + \omega_2)$, $(2\omega_2 + \omega_1)$, $(2\omega_1 - \omega_2)$ and $(2\omega_2 - \omega_1)$. Out of these signals, the most problematic are $(2\omega_1 - \omega_2)$ and $(2\omega_2 - \omega_1)$ and the signals at these frequencies are known as third-order intermodulation products. Observing these second-order and third-order frequency terms, it is evident that higher order terms will be sum or difference of integer multiples of ω_1 & ω_2. So, in general all possible distortion terms in output of amplifier can be calculated by using the term $\alpha\omega_1 \pm \beta\omega_2$, where α & β are integers. Therefore, fifth-order intermodulation products will appear at the frequencies of $(3\omega_1 - 2\omega_2)$ & $(3\omega_2 - 2\omega_1)$ and seventh-order intermodulation products will be present at the frequencies of $(4\omega_1 - 3\omega_2)$ & $(4\omega_2 - 3\omega_1)$. These intermodulation products are a major concern and need to be removed to ensure linearity. The Table 1 below shows the different IMD products.

Table 1 Intermodulation products

Order	Intermodulation Products	
	Low Side	High Side
3	$2\omega_1 - \omega_2$	$2\omega_2 - \omega_1$
5	$3\omega_1 - 2\omega_2$	$3\omega_2 - 2\omega_1$
7	$4\omega_1 - 3\omega_2$	$4\omega_2 - 3\omega_1$

III. FEEDFORWARD LINEARIZATION

The first ever linearization method for RF power amplifiers was invented in 1923 by Howard Black of Bell Telephone Laboratories [15] popularly known as feedforward linearization. The motivation behind this invention came while he was working to minimize distortion in multiplex telephone systems where multiple amplifiers' distortion may sum together and degrade the output audio signal [16].

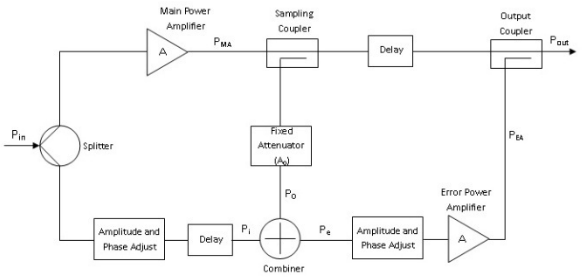

Fig. 2 Feedforward technique

The block diagram of feedforward linearization method is shown in Fig. 2 [9]. There are two loops; first loop is signal cancellation loop and second is error cancellation loop. The input signal P_{in} in the first loop is amplified by main power amplifier giving P_{MA}. The amplifier output consists of amplified input signal and intermodulation distortion products generated due to amplifier's non-linearity i.e.,

(11)

where, A is gain of main power amplifier and is the intermodulation distortion.

Fixed attenuator with attenuation factor then brings down this amplified signal, making it equal to input signal itself plus the distortion.

(12)

Since, the value of fixed attenuator is chosen to match the gain of main power amplifier [8], so . Therefore, changing the denominator of first term of (12) we get,

(13)

This signal in (13) is then combined with attenuated, phase adjusted and delayed lower branch signal giving the error signal consisting of only distortion.

(14)

where, and is the phase shift introduced by phase shifter. Therefore, (14) becomes,

(15)

Now, we know that input is delayed in phase, so we have or and therefore the error signal becomes,

(16)

The error signal is then phase shifted giving and amplified by error amplifier by an equal amount with which the main amplifier output was attenuated giving amplified error signal,

(17)

And then this signal is combined with delayed amplifier output signal, thereby finally giving linearized, distortion-less signal at the output.

(18)

()

The amplitude and phase shifters having broadband tunable characteristics are the main components that make the necessary adjustments so as to obtain minimum intermodulation distortion levels [17].

IV. SIMULATION AND RESULTS

The implementation of simulation circuit for feedforward linearization of 16W WCDMA multicarrier power amplifier [13] is shown in Fig. 3.

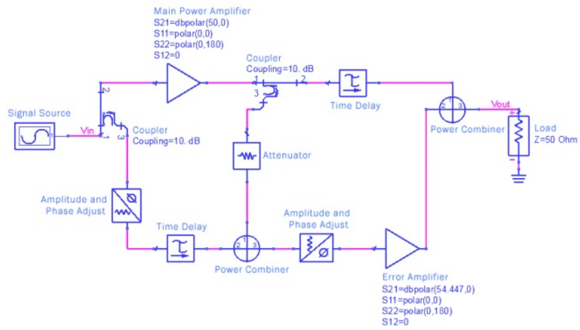

Fig. 3 Feedforward linearization circuit

4.1 Measurement of Intermodulation Distortion and Carrier to IMD power ratio (C/I)

For the measurement of amount of IMD cancellation, we used two-tone test. The simulation circuit for two-tone analysis is shown in Fig. 4. The fundamental frequency of the input signal is taken as RFfreq = 2125 MHz, the spacing between carriers is chosen as f_c = 10 MHz. Therefore, the frequencies of two tones (f_1 and f_2) and the third-order, fifth-order and seventh-order IMD products are calculated as,

Input carriers:

3rd-order IMD:

5th-order IMD:

7th-order IMD:

Firstly, the simulation is carried out at the input power level of -8 dBm near the saturation and 1dB compression point to calculate the new IMD levels and then the input power is varied to analyze how the intermodulation distortions are affected as the input power is changed.

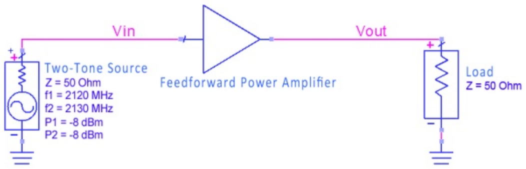

Fig. 4 Two-tone analysis setup

Before applying any linearity circuit, the output of the amplifier is obtained as shown in Fig. 5.

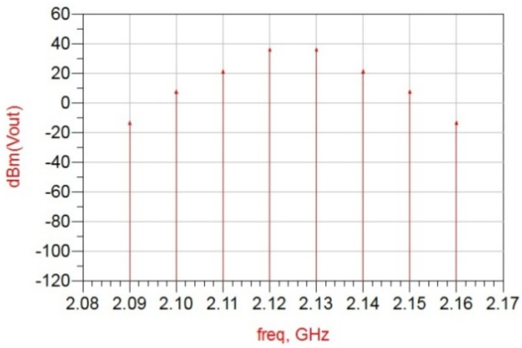

Fig. 5 IMD in amplifier output before linearization

The output of amplifier after applying linearity method is shown in Fig. 6.

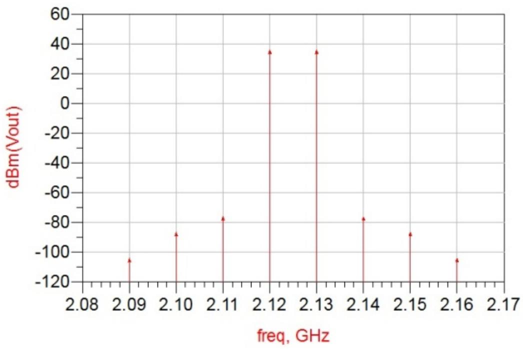

Fig. 6 Reduced IMD in amplifier output after linearization

Therefore, from Fig. 5 & Fig. 6, we examine a great decrease in the amount of intermodulation distortion. Comparison between IMD values before and after linearization is given in Table 2 and Table 3 gives the comparison of C/I i.e. distance between intermodulation distortion and carrier signal values.

Table 2 IMD before and after linearization

Order	Intermodulation distortion (dBm)			
	Before linearization		After linearization	
	Low side	High side	Low side	High side
3	22.443	22.444	-76.240	-76.240
5	8.849	8.845	-86.819	-86.817
7	-12.237	-12.170	-104.307	-104.274

Table 3 C/I before and after linearization

Order	C/I (dB)			
	Before linearization		After linearization	
	Low side	High side	Low side	High side
3	14.605	14.605	112.236	112.237
5	28.200	28.203	122.816	122.814
7	49.285	49.218	140.304	140.271

4.2 Intermodulation Distortion with swept power

To determine how intermodulation distortion alters as we sweep the input power of both the carriers, we apply a sweep of RF power within the range of -20 dBm to 20 dBm and make a comparison for non-linearized and linearized amplifier through graphs. Fig. 7, Fig. 8 and Fig. 9 give the comparison of 3rd-order, 5th-order and 7th-order IMD variations with input power.

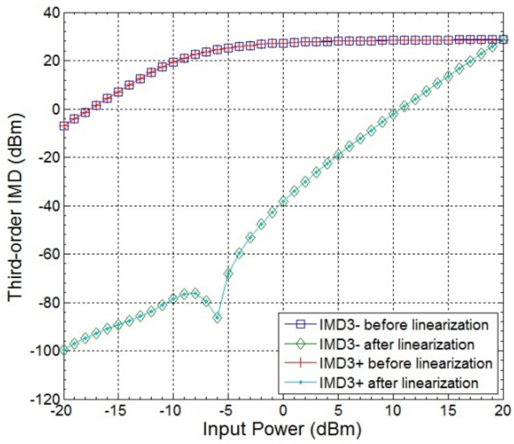

Fig. 7 Variation of 3rd-order IMD with input power

In Fig. 7, we observe that while the 3rd-order IMD before linearization at lowest input power of -20 dBm was -7.138 dBm on both high and low side, it is -99.518 dBm on high and low side of original carriers after linearization. It suddenly falls to value of -86.431 dBm on low side and -86.423 dBm on high side at -6 dBm of input power and then increases as we increase the input power.

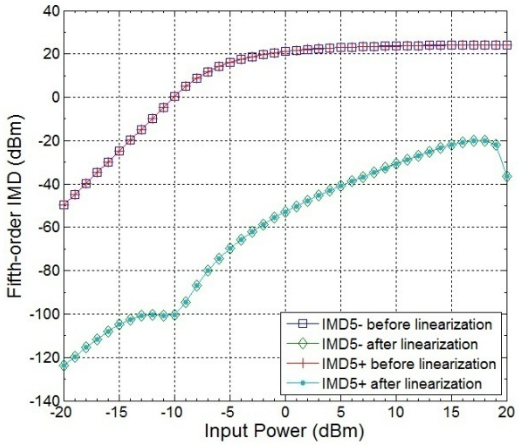

Fig. 8 Variation of 5th-order IMD with input power

Fig. 8 shows that 5th-order IMD which was -49.800 dBm at lowest input power of -20 dBm on both low and high side before linearization has now reduced to -123.895 dBm after linearization. At input power between -13 dBm & -10 dBm, it almost remains constant at -100 dBm approximately and after -10 dBm it increases with increase in input power but always remains at lower levels as compared to the non-linearized case.

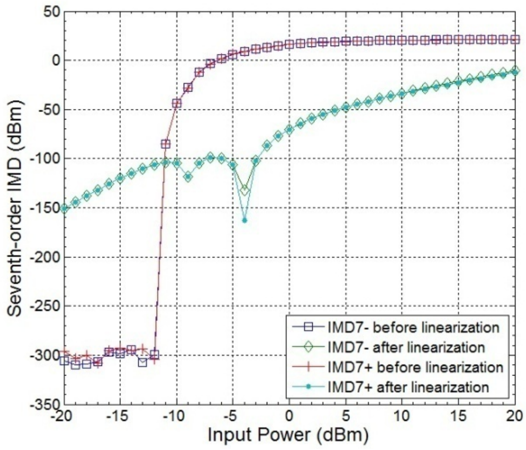

Fig. 9 Variation of 7th-order IMD with input power

In Fig. 9, it is noticed that 7th-order IMD was lowest before linearization upto -12 dBm of power input. But after that it increases gigantically at input power level of -11 dBm from -304.221 dBm at -12 dBm to -85.453 dBm at -11 dBm and increases afterwards. Whereas, after linearization it is higher below input power of -12 dBm and becomes lower after that as compared to the case when no linearity method was applied and remains less up to 20 dBm power input. Therefore, 7th-order IMD decrease is spotted after power level of -12 dBm. The Table 4 below gives IMD values for different input powers.

Table 4 IMD values at different input powers for FF amplifier

IMD (dBm)	Input Power (dBm)				
	-20	-10	0	10	20
IMD3-	-99.518	-78.651	-38.287	-2.206	28.842
IMD3+	-99.518	-78.651	-38.287	-2.206	28.842
IMD5-	-123.895	-100.250	-52.848	-30.684	-36.373
IMD5+	-123.895	-100.250	-52.854	-30.719	-36.339
IMD7-	-151.093	-104.565	-70.109	-33.606	-10.804
IMD7+	-151.093	-104.565	-70.149	-33.965	-12.095

4.3 Measuring the Input and Output Intercept Points

The input and output intercept points play a very crucial role as linearity determinant. Higher intercept points are always preferred. So, we used the similar two-tone analysis method previously applied to determine IMD suppression. The simulation gave the values of input and output intercept points up to seventh order. Table 5 and Table 6 give the calculated values at input power of -8 dBm.

Table 5 Intercept Points of nonlinear amplifier

Order	Intercept Points (dBm)			
	Input		Output	
	Low side	High side	Low side	High side
3	-3.708	-3.708	44.351	44.350
5	-3.960	-3.959	44.098	44.099
7	-2.796	-2.807	45.262	45.251

Table 6 Intercept Points of feedforward amplifier

Order	Intercept Points (dBm)			
	Input		Output	
	Low side	High side	Low side	High side
3	45.108	45.108	92.115	92.115
5	19.694	19.693	66.701	66.700
7	12.374	12.368	59.381	59.375

4.4 Intercept points with swept power

To observe the intercept points at different power measures we apply a sweep of input power in the range of -20 dBm to 20 dBm and compare the results with nonlinear amplifier. Fig. 10, Fig. 11 and Fig. 12 give the input intercept points of different orders.

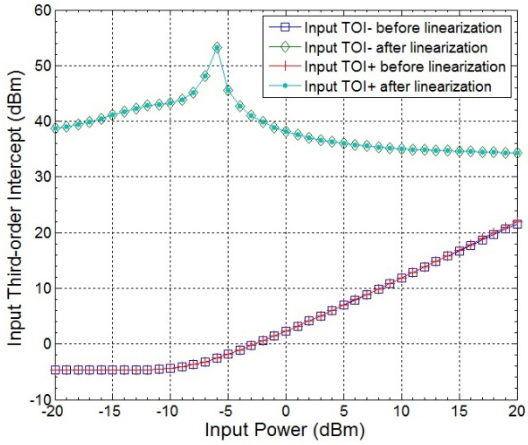

Fig. 10 Input TOI

The graph shows an increase in input third-order intercept point for feedforward amplifier. At -20 dBm of input power it is 38.747 dBm as compared to -4.628 dBm of nonlinear amplifier. It is hiked at input power of -6 dBm with a value of 53.203 dBm on lower side and 53.199 dBm on higher side.

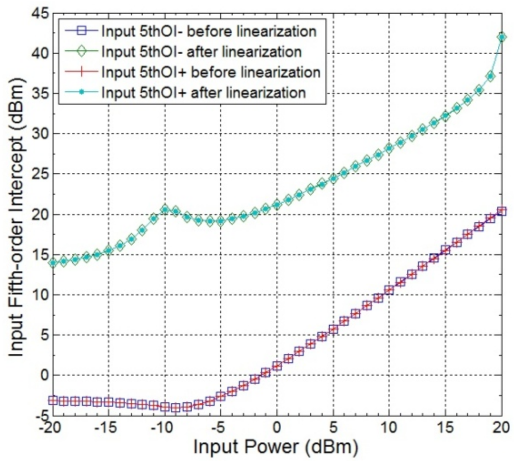

Fig. 11 Input 5thOI

In 5thOI graph, it is clearly seen that feedforward amplifier has much higher values of 5thOI than nonlinear amplifier. At input power of -20 dBm, it has increased from -3.154 dBm for nonlinear amplifier to 13.963 dBm for FF amplifier. It experiences a bump at -10 dBm of input power with a value of 20.551 dBm on lower side and 20.552 dBm on higher side and then it further increases with increase in input power. One must notice here that the values of input 5th-order intercepts obtained after linearization are always greater than the values measured before linearization. That is why the graph is increasing upwards and is always higher than the case with no linearization applied.

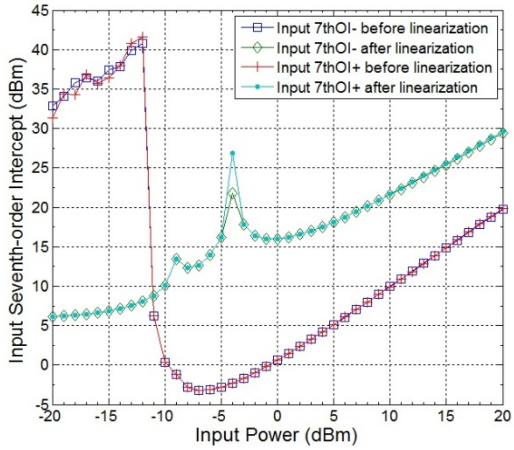

Fig. 12 Input 7thOI

The above graph shows that input seventh-order intercept after linearization is firstly less up to -12 dBm, after that it increases as compared to the case when no linearization was applied. It experiences a sudden increase at -4 dBm input power and remains high for linearized case afterwards. Therefore, from all the graphs for input intercept points we conclude that input TOI and 5thOI are always higher for feedforward amplifier whereas input 7thOI only increases after -12 dBm of input power. Now, we will see how output intercept points behave as we vary RF power input. Fig. 13, Fig. 14 and Fig. 15 show the output intercept points of third-order, fifth-order and seventh-order respectively.

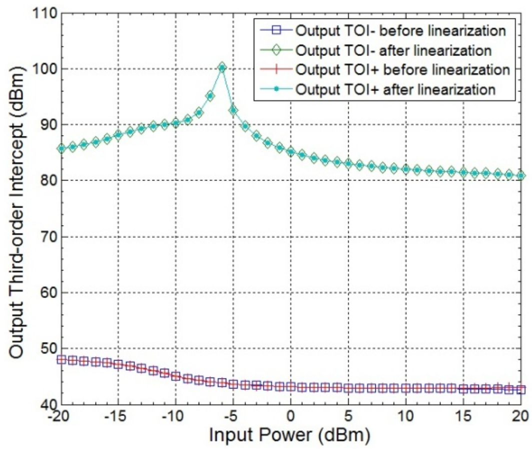

Fig. 13 Output TOI

Fig. 13 shows the variation of output third-order intercept point with input power. Feedforward amplifier always has large values of TOI than nonlinear amplifier. There is a peak in output TOI for FF amplifier at input power of -6 dBm having value of 100.210 dBm on lower side and 100.207 dBm on higher side.

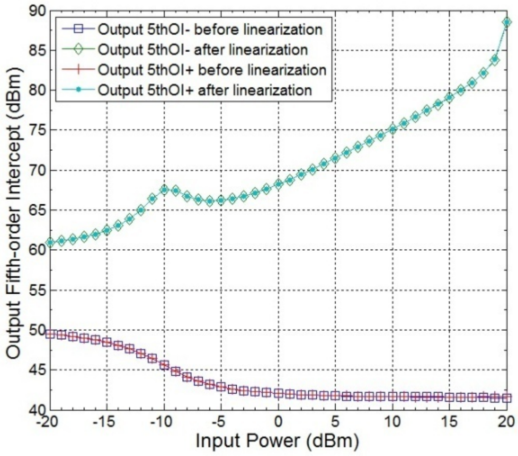

Fig. 14 Output 5thOI

The above graph gives output fifth-order intercept point before and after linearization at different power levels. While 5thOI for nonlinear amplifier is decreasing as input power is increased, 5thOI for FF amplifier increases with input power.

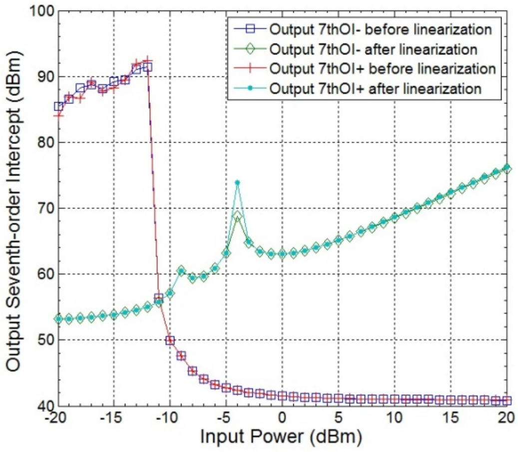

Fig. 15 Output 7thOI

In Fig. 15, we see that up to input power of -12 dBm, the output seventh-order intercepts for feedforward amplifier are lower than nonlinear amplifier but after that it increases. Also, it experiences a sudden increase at -4 dBm input power with values 68.755 dBm on lower side and 73.855 dBm on higher side. Therefore, we here deduce that like input intercept points, output 3rd-order and 5th-order intercept points are also higher for feedforward amplifier but output 7th-order intercept point increase only after -12 dBm of input power. Hence, we can say that input intercept points and output intercept points of all orders behave somewhat alike after linearization. The Table 7 below gives input and output intercept point's values for different input powers.

Table 7 Intercept Points for FF amplifier at different input powers

Intercept Point (dBm)		Input Power (dBm) -20	-10	0	10	20
Input	TOI-	38.747	43.313	38.131	35.074	34.340
	TOI+	38.747	43.313	38.131	35.073	34.340
	5thOI-	13.963	20.551	21.201	28.151	41.969
	5thOI+	13.963	20.552	21.202	28.160	41.960
	7thOI-	6.171	10.083	16.007	21.584	29.381
	7thOI+	6.171	10.083	16.014	21.644	29.596
Output	TOI-	85.754	90.321	85.137	82.045	80.893
	TOI+	85.754	90.321	85.137	82.045	80.893
	5thOI-	60.970	67.559	68.206	75.123	88.522
	5thOI+	60.970	67.559	68.208	75.132	88.513
	7thOI-	53.178	57.091	63.013	68.556	75.934
	7thOI+	53.178	57.090	63.020	68.616	76.149

Therefore, by feedforward analysis we have been able to decrease distortion and increase linearity of amplifier.

V. CONCLUSION

The effectiveness in linearity improvement has been depicted by using feedforward linearization technique. The suppression in intermodulation distortion has been calculated using two-tone method. The results show that the lower 3rd-order, 5th-order and 7th-order IMD have been reduced by 98.683 dBm, 95.668 dBm and 92.070 dBm respectively and higher 3rd-order, 5th-order and 7th-order IMD have been reduced by 98.684 dBm, 95.662 dBm and 92.104 dBm respectively. By varying RF input power it is also concluded that the IMD of third and fifth orders are always less than nonlinear amplifier and increase with input power increase. But, IMD of seventh-order shows a decrease after -12 dBm of input power. The C/I ratios have also been measured to make a comparison of fundamental and IMD power levels. It is increased by 97.631 dB for 3rd-order, 94.616 dB for 5th-order, 91.019 dB for 7th-order on lower side and 97.632 dB for 3rd-order, 94.611 dB for 5th-order, 91.053 dB for 7th-order on higher side of fundamental carriers. The input and output intercept points are also measured and observed a major increase in comparison to previous nonlinear case. The lower input 3rd-order, 5th-order, 7th-order intercepts have been increased by 48.816 dBm, 23.654 dBm, 15.170 dBm and higher input 3rd-order, 5th-order, 7th-order intercepts have been increased by 48.816 dBm, 23.652 dBm, 15.175 dBm. For output 3rd-order, 5th-order, 7th-order intercepts we have seen increment by values of 47.764 dBm, 22.603 dBm, 14.119 dBm on lower side and on higher side of fundamental carriers the increment is 47.765 dBm, 22.601 dBm, 14.124 dBm for output 3rd-order, 5th-order, 7th-order intercepts respectively. Moreover, by varying RF input power it is observed that both IMD and intercept points are always better after -12 dBm of input power. Therefore, the feedforward linearized power amplifier will give best results in terms of IMD cancellation and intercept point increase when operated around and above power levels of -12 dBm.

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