Linearizing of Low Noise Power Amplifier Using 5.8GHz Double Loop Feedforward Linearization Technique

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Abstract

In this paper, a double loop feedforward linearization technique is analyzed and built with a MMIC low noise amplifier "HMC753" as main amplifier and a two-stage class-A power amplifier as error amplifier. The system is operated with 5V DC supply at a center frequency of 5.8GHz and a bandwidth of 500MHz. The proposed technique, increases the linearity of the MMIC amplifier from 18dBm at 1dB compression point to more than 26dBm. In addition, the proposed system is tested with OFDM signal and it reveals good response in maximizing the linearity region and eliminating distortions. The proposed system is designed and simulated onAdvanced Wave Research-Microwave Office (AWR-MWO).

Keywords : feedforward , linearization techniques , power amplifier , RF amplifier.

الخلاصة

في هذا البحث، تم تحليل وتصميم تقنية التغذية الأمامية المزدوجة بأستخدام مكبر القدرة قليل الضوضاء "HMC753" الذي يمثل مكبر القدرة الرئيسي في هذه التقنية. إضافة إلى ذلك، صُمم مكبر قدرة من نوع A ليُكبر إشارة الخطأ، الذي هو مكون من مرحلتين ليملك نسبة تكبير تساوي تقريبا نسبة تكبير المكبر الرئيسي. يعملهذا النظام بفولتية مجهزة تساوي 5V، بتردد 5.8GHz، وبحزمة ترددية تساوي 500MHz. حيث أن التقنية المقترحة تُزيد خطية المكبر الرئيسي من 18dBm إلى أكثر من 26dBm. وقد تم فحص إشارة OFDM في هذه التقنية وأعطت أستجابة جيدة في زيادة المنطقة الخطية وحذف التشوهات. تم هذا العمل بأستخدام برنامج Advance Wave Research–Microwave Office (AWR–MWO).

الكلمات المفتاحية : التغذية الأمامية ، التقنيات الخطية ، مكبر القدرة ، المكبرات الراديوية

1. Introduction

In modern radio telecommunication systems, the trend is towards multicarrier transmitters, where a single amplifier handles several carriers simultaneously, in which the bandwidth, power level, and the peak power to average power ratio all increase, thus, the design of economical power amplifier for these requirements is a real engineering challenge. The high efficiency of a power amplifier is important because it leads to increase the output power, battery lifetime, and reliability of wireless transmitters, but this leads to reduce the linearity and produce distortion at the output of the power amplifier. The distortion in the response of a power amplifier causes several unwanted effects like difficulty in receiver operation and spectral re-growth which is represented by the signal expansion into adjacent channels. Therefore, the type of a power amplifier must be chosen according to the linearity and efficiency requirements of the communication system. The linearization techniques are useful for modern communication systems that use complicated modulation techniques and multicarrier schemes. These modern systems have high peak to average power ratio (PAPR), therefore, they need linear amplification to prevent the distortion generated due to high PAPR. But, linear power amplifiers have very low efficiency especially very high power amplifiers. Also the cost of a power amplifier is high because this amplifier must operate in high back off power to ensure that it operates in linear mode. Here, linearization techniques become very important to handle these problems. There are three main linearization techniques, which are: feedback, pre-distortion, and feedforward techniques [Cripps, 2006].

Among various linearization methods, the feedforward linearization technique is a fairly established principle offering a good trade-off between linearity and power-efficiency even under wideband operation. The Feedforward linearization technique was firstly innovated in 1928 by H.S. Black. High frequency and broadband requirements of rapidly progressing communication systems, led to insisting interests for developing techniques based on feedforward concept. It almost was forgotten for a half century. Then, implementations of feedforward concepts were resumed again in 1971 by Seidel. He used it to linearize a TWT-based amplifier developed later in 1974 by Bennett. The Feedforward amplification technique has re-emerged as one of the most active technical topics in the wireless communication era [Cripps, 2006].

To demonstrate the behaviour of the feedforward linearization technique, [Cho and stapleto, 2005; Haydee *et.al.,* 2006; hati *et. al.,* 2006; Jeong *et. al.,* 2006; Ma and Feng, 2007; Hemmatyar and Farzaneh, 2007; Liao *et.al.,* 2008; Honarvar *et. al*., 2009; Suzuki et. al., 2011; Taravati and Tayarani, 2013; Gharaibeh and Al-Zayed, 2015] had introduced many feedforward linearization systems with different types of main and error amplifiers at several centre frequencies using multi-carrier transmissions (OFDM and W-CDMA). [Thandri and Silva-Martinez, 2003; Szczepanski and Kozeil, 2004] used OTA for offering a better performance of phase compensation. In addition, various adaptive methods were used with feedforward technique to control the error cancellation loop for better intermodulation distortion (IMD) suppression at a number of frequencies [Kurt and Polamutcuogllari, 2006; Braithwaite, 2008; O'Conner *et. al.,* 2008; Keehr and Hajimiri, 2008; Kwon and Eun, 2009; Gokceoglu *et.al*., 2012; Braithwaite and Khanifar, 2013; Neo *et. al.,* 2014; Gallaghera *et. al.,* 2014].

Among numerous techniques for linearizing power amplifiers, feedforward technique is widely used in the design of base station amplifiers due to its intrinsic advantage in achieving high linearity, unconditional stability, much broader correction bandwidth, and operation at high center frequencies compared with other techniques. In this work, feedforward linearization technique is adopted due its wide range of linearization. A double loop system using this technique is adopted at 5.8GHz center frequency for Base station applications.

2. Analysis of the proposed double loop feedforward linearization technique

Before analyzing the proposed double loop feedforward linearization technique, the basic feedforward linearization technique (FFLT) should be first stated and analyzed.The basic FFLT is shown in Figure 1. It has two loops. The first loop is called the main signal cancellation loop, which extracts the error signal represented by the inter-modulation distortion (IMD) components and other harmonic components from the main amplifier (MA) output, while the second loop is called the error signal cancellation loop, which inverts and amplifies the error signal by an auxiliary amplifier, called error amplifier (EA) such that it can be cancelled at the feedforward amplifier output.

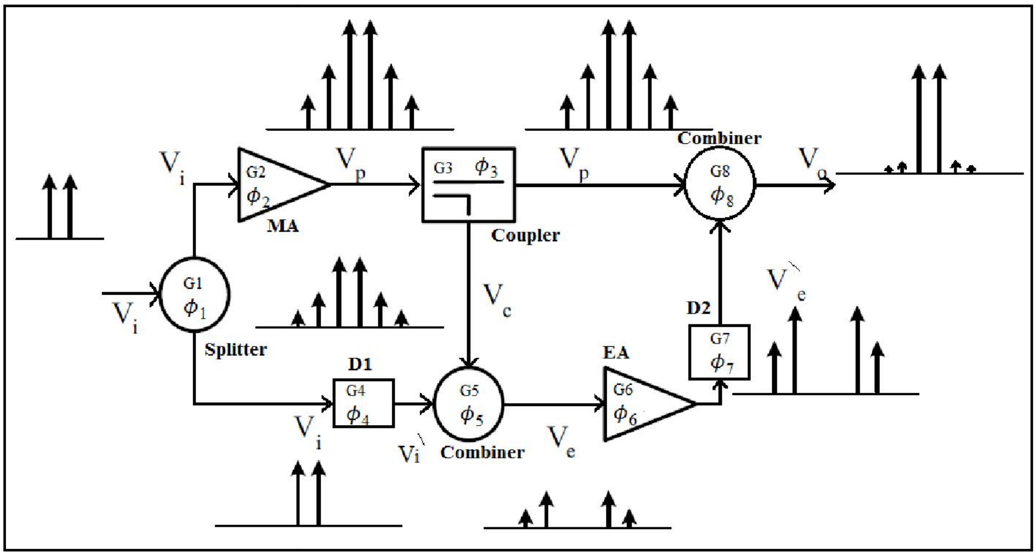

Figure 1. The basic FFLT.

The scheme consists of two cancellation loops. Each item in these loops is characterized by a Gain G in dB and phase shift ϕ in degrees. This linearization technique is an open loop and unconditionally stable, so theoretically suitable for any wideband application. The main signal cancellation loop is designed to cancel the main signal and extract the error signal from the main amplifier. The distorted output signal V_P of MA contains a linearly amplified portion of the original signal $V_i$associated with a non-linear distortion component V_d [Cripps, 2006; and Haydee *et.al.*, 2006]. It can be given by

$$V_P = V_i 10^{\frac{G_1+G_2}{20}} e^{j(\phi_1+\phi_2)} + V_d \quad (1)$$

The amplifier output signal passes through a coupler to couple some of the power. The coupled signal V_C is of such a magnitude that it matches the reference signal. The original signal V_i is delayed through the delay line D_1such that its output V_i' is out of phase with V_C. Then both V_i' and V_C are applied to power combiner of main signal cancellation loop. The following equations can be written for describing the operation of this loop [Haydee *et. al.,*2006; Jeong *et.al.,*2006; and Honarvar *et. al.,* 2009]:

$$V_c = V_P 10^{\frac{G_3}{20}} e^{j\phi_3} = V_i 10^{\frac{G_1+G_2+G_3}{20}} e^{j(\phi_1+\phi_2+\phi_3)} + V_d 10^{\frac{G_3}{20}} e^{j\phi_3} \quad (2)$$

Since,$G_3 = -G_2$, then,

$$V_c = 10^{\frac{G_1}{20}} e^{j(\phi_1+\phi_2+\phi_3)} + V_d 10^{\frac{G_3}{20}} e^{j\phi_3} \quad (3)$$

$$V_i' = V_i 10^{\frac{G_1+G_4}{20}} e^{j(\phi_1+\phi_4)} \quad (4)$$

$$V_e = \left(V_c + V_i'\right) 10^{\frac{G_5}{20}} e^{j\phi_5} \quad (5)$$

Since,$\phi_2$and$\phi_4$are out of phase, then they cancel each other. The splitter, coupler, and power combiner have zero phase shifts. This results in $\phi_1 = \phi_3 = \phi_5 = 0$. Also, the splitter, the delay line, and the power combiner have zero gains, i.e.,$G_1 = G_4 = G_5 = 0$. Thus, the expression of $V_e$can be reduced to

$$V_e = V_d 10^{\frac{G_3}{20}} \quad (6)$$

The error cancellation loop shown in Figure 1 is designed in such a manner that it will amplify the error signal by the EA so that it can be injected back into the output power combiner as -V_d. This can be accomplished as follows:

$$V_e' = V_d 10^{\frac{G_3+G_6+G_7}{20}} e^{j(\phi_6+\phi_7)} \quad (7)$$

Since, $V_e^{'}$ should be injected in the output combiner as $-V_d$, then $G_3 + G_6 + G_7$ should be equated to zero and $\phi_6 + \phi_7$ should be equated to ±π. Since, the delay line has zero gain, then $G_7 = 0$and $G_6 = -G_3$. Eventually, the expression of $V_e^{'}$ is reduced to

$$V_e^{'} = V_d e^{\pm j\pi} \tag{8}$$

The error loop output is combined into the main signal path and the main amplifier's distortion products are cancelled. The output of the whole amplifier V_o can be given by

$$V_o = \left(V_p + V_e^{'}\right) 10^{\frac{G_8}{20}} e^{j\phi_8} \tag{9}$$

Since, the output combiner has zero gain and zero phase shift, then $G_8 = 0$ and $\phi_8 = 0$. Finally Equation 9 can be reduced to

$$V_o = V_i 10^{\frac{G_2}{20}} e^{j\phi_2} + V_d + V_d e^{\pm j\pi} = V_i 10^{\frac{G_2}{20}} e^{j\phi_2} \tag{10}$$

After the cancellation of the distortion, a linearly amplified signal of the original input signal will be available at output of the feedforward amplifier [Honarvar *et. al.,* 2009].

The Double loop FFLT is used here for increasing the linearity of the power amplifier more than the basic FFLT does. The structure of double loop FFLT is shown in Figure 2. In this figure, loops (1), (2), (3), and (4) represent the first main signal cancellation loop, the first error cancellation loop, the second main signal cancellation loop, and the second error cancellation loop, respectively. Loops (1) and (2) in this system, represent the Basic FFLT shown in Figure 1. Applying the same approach used for analyzing the basic FFLT and taking into account that V_P in Figure 1 represents V_{o1} in the proposed double loop FFLT, the output of the proposed system V_{o2}can be given by

$$V_{o2} = V_i 10^{\frac{G_2}{20}} e^{j\phi_2} \tag{11}$$

The parameters in the above structures that can be tuned, are the coupling factor of the first coupler (k_1), the first delay line (D_1), the second delay line (D_2), the coupling factor of the second coupler (k_2), the third delay line (D_3), and the fourth delay line (D_4).

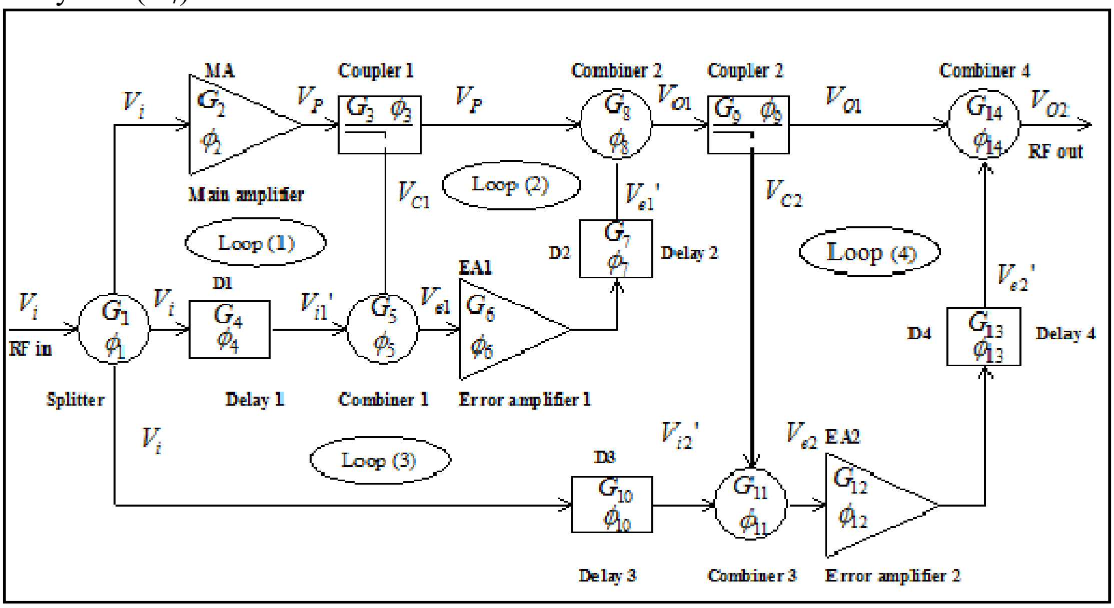

Figure 2. The Double loop FFLT.

3. Circuit design of the proposed system

To show the feasibility of the proposed double loop FFLT, a MMIC low noise amplifier was linearized using this technique. The MMIC low noise amplifier is of a type of HMC753. This amplifier is a class-A amplifier and in the frequency range of 1 GHz to 6 GHz is characterized by Gain=16.5 dB, Output power for 1 dB compression (P1dB) = 18 dBm, Output third-order intercept (IP3) = 30 dBm, 50 Ω matched input/output (I/O), supply voltage (VDD) = 5 V at 55 mA, saturated output power (PSAT) = 20 dBm, and Noise figure= 1.5 dB. This amplifier was considered as a main amplifier in the proposed FFLT system, while the error amplifier was designed as two-stage class-A amplifier.

The first stage of the proposed error amplifier was built using the RF NPN BJT “NESG2021M16” while the second stage was built with the RF NPN BJT “NESG3031M14”. The amplifier was driven by a DC voltage source of 5V. The first stage was biased with a collector current of 10 mA while the second stage was biased with a collector current of 25 mA. Each stage was designed at a center frequency of 5.8 GHz and a bandwidth of 500 MHz. The selected center frequency and bandwidth for this amplifier had resulted in a quality factor of 11.6 taking into account 50 Ω resistive load. Figure 3 shows the circuit diagram of this amplifier carried out on Advanced Wave Research-Microwave Office(AWR-MWO) taking into account the impedance matching of 50 Ω for the input and output circuits of each stage of this amplifier.

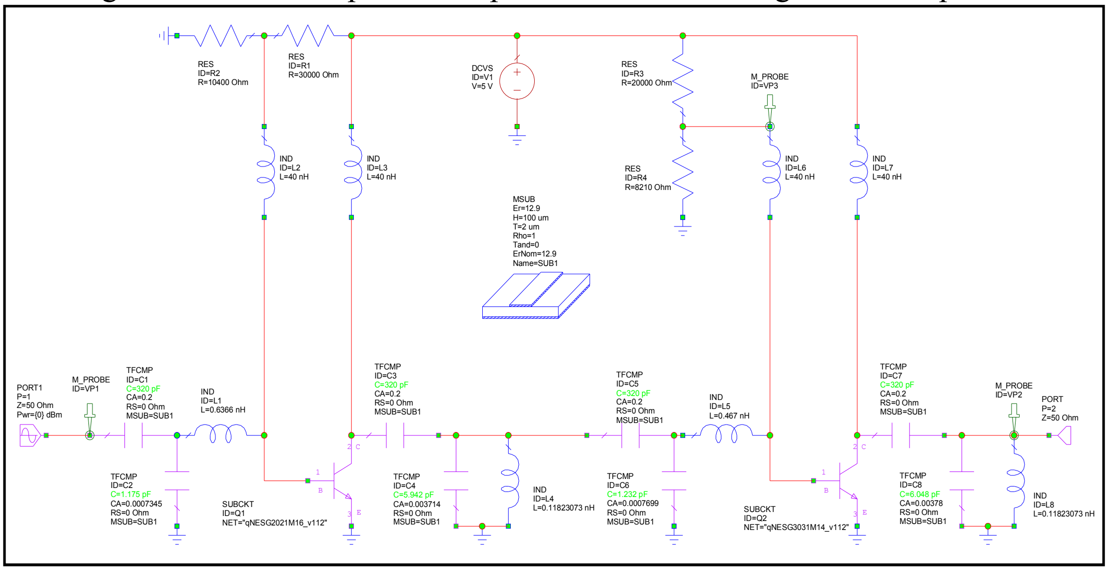

Figure 3. The circuit schematic of class-A PA.

The system diagram of the proposed double loop FFLT is shown in Figure 4. It is also designed onAWR-MWO.

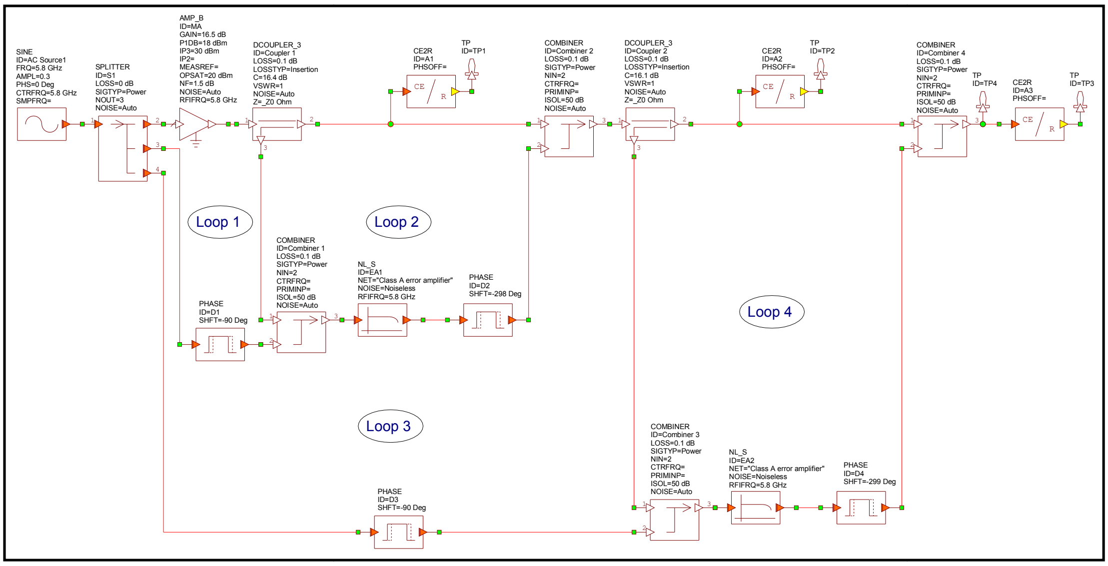

Figure 4. The circuit diagram of the proposed double loop FFLT system for linearizing a MMIC low noise amplifier using a 2-stage class-A power amplifier as error amplifier.

4. Simulation results

The MMIC "HMC753" was tested on AWR-MWO for checking linearity using what is known in this program as theAM-AM test. The result of this test is shown in Figure 5.

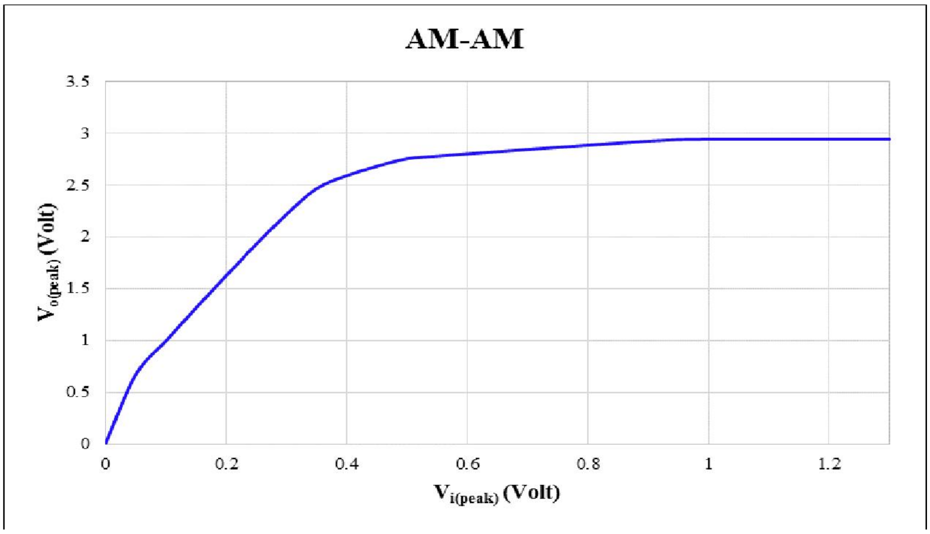

Figure 5. The AM-AM characteristics of the MMIC "HMC753" amplifier at an operating frequency of 5.8 GHz.

The error amplifier designed for linearizing the MMIC "HMC753" was tested on AWR-MWO to show its linearity at a frequency 5.8 GHz.Its AM-AM characteristics is shown in Figure 6.

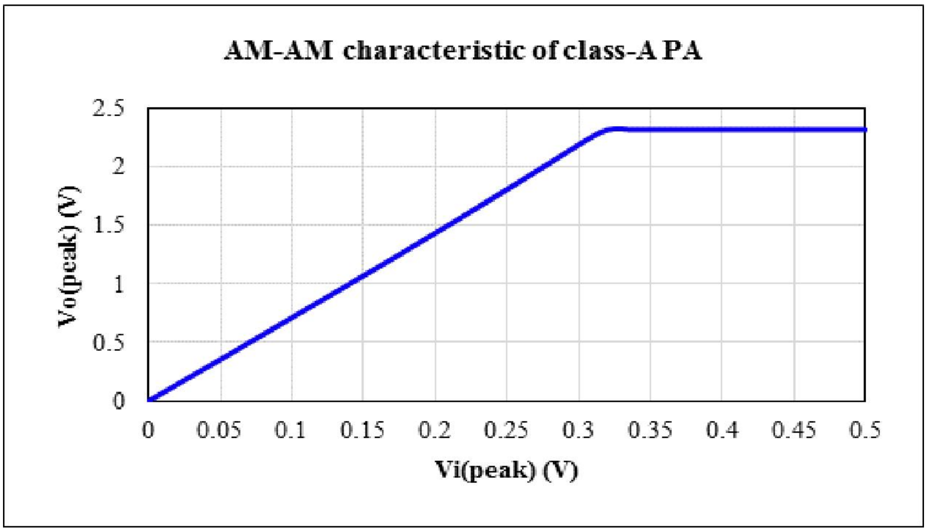

Figure 6. AM-AM characteristics of the proposed class-Aerror amplifier.

Three important single tone tests at 5.8 GHz were carried out to investigate the linearization capability of the proposed FFLT shown in Figure 4. The first test was carried out in the linear region of the main amplifier, the second was carried out in the linear region of the basic loop, and the third was carried out at the end point of the second loop linear region.Figure 7, Figure 8, and Figure 9 show the output voltage waveforms corresponding to these three tests.

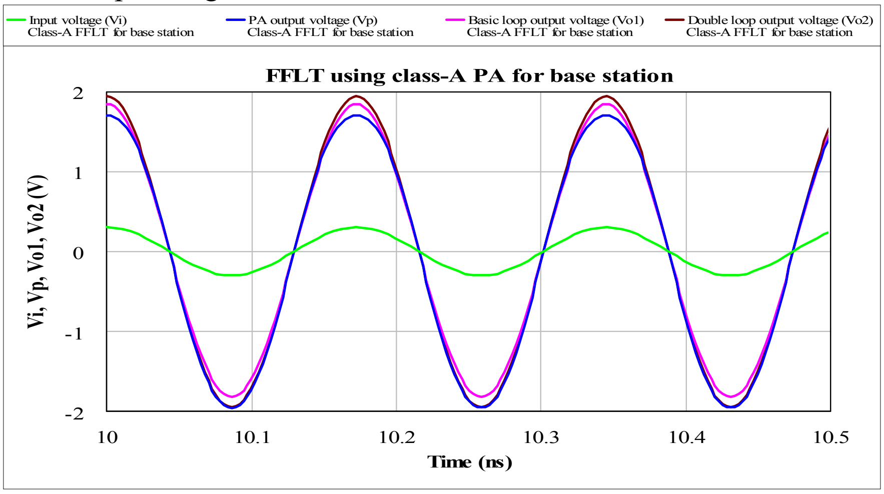

Figure 7. The voltage waveforms of the proposed double loop FFLT with input voltage of 0.3V (peak value).

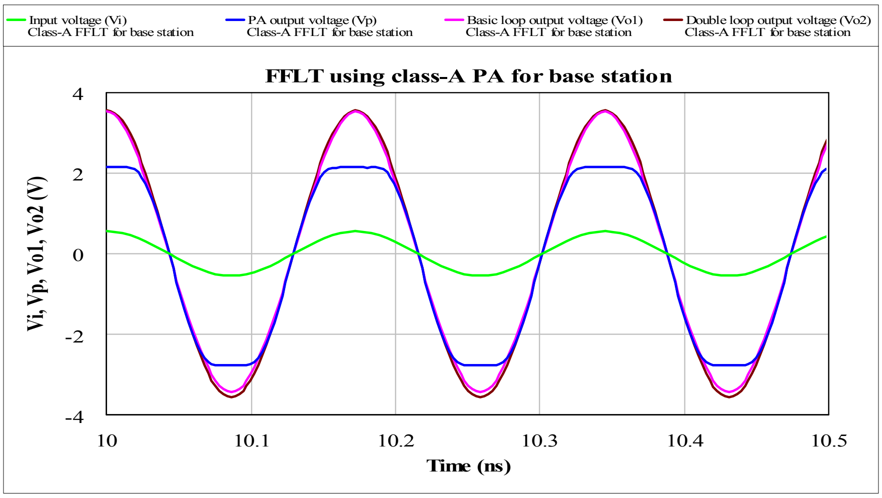

Figure 8. The voltage waveforms of the proposed double loop FFLT with input voltage of 0.55V (peak value).

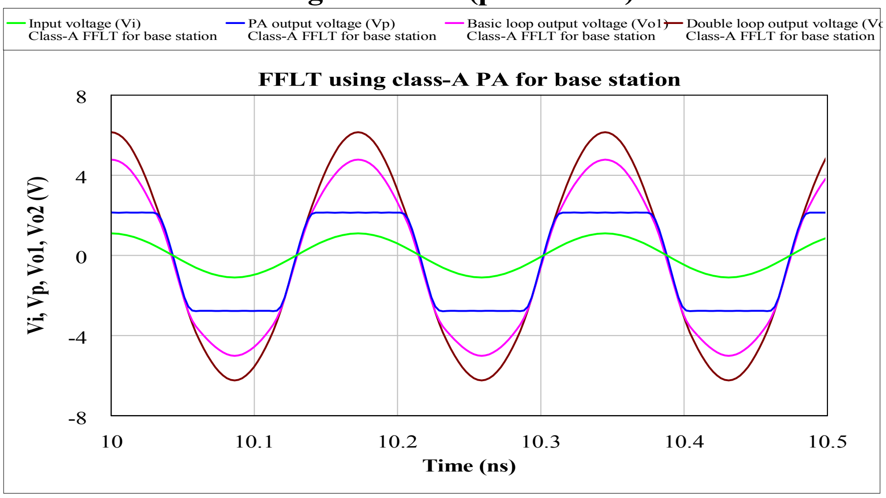

Figure 9. The voltage waveforms of the proposed double loop FFLT with input voltage of 1.1V (peak value).

Figure 10 shows AM-AM test of the proposed double loop FFLT. The figure reveals that both basic FFLT and the proposed double FFLT have participated in increasing the linearity of the low noise MMIC “HMC753”.

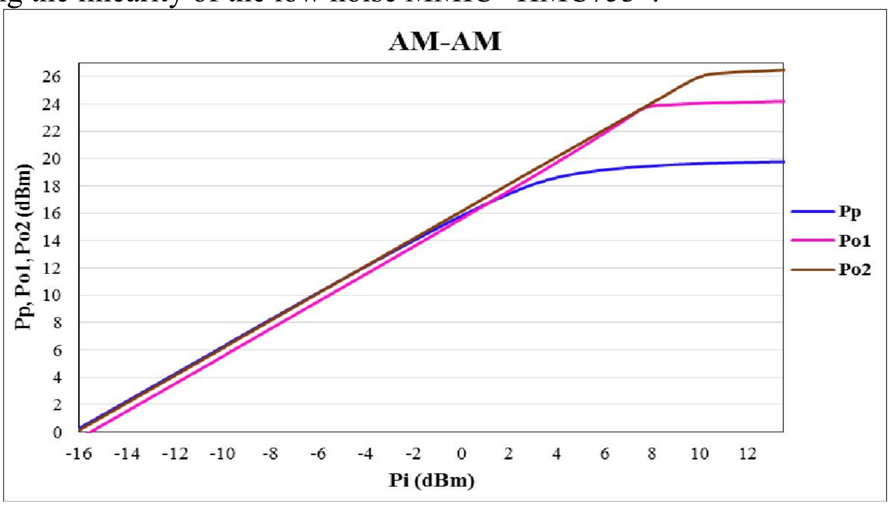

Figure 10. The AM-AM response of the main amplifier, basic loop, and second loop of the proposed double loop FFLT.

With 2-tone test that is separated from each other by 200 MHz at the centre frequency of 5.8 GHz, three test were carried out to investigate the system linearization capability and cancellation ranges of intermodulation distortions. The first test was carried out using a two-tone input of -3.98 dBm.

Figure 11, Figure 12, and Figure 13 show the output power spectrums of the main amplifier, the basic FFLT, and the double loop FFLT, respectively.Figure 11 exhibits main signal power of 11.7 dBm associated with maximum intermodulation distortion of -19.62 dBm in the vicinity of the main signal spectrum,Figure 12 exhibits main signal power of 11.69 dBm associated with maximum intermodulation distortion of -38.35 dBm in the vicinity of the main signal spectrum, and Figure 13 exhibits main signal power of 12.17 dBm associated with maximum intermodulation distortion of -58.41 dBm in the vicinity of the main signal spectrum. No significant linearization is noticed in this test.

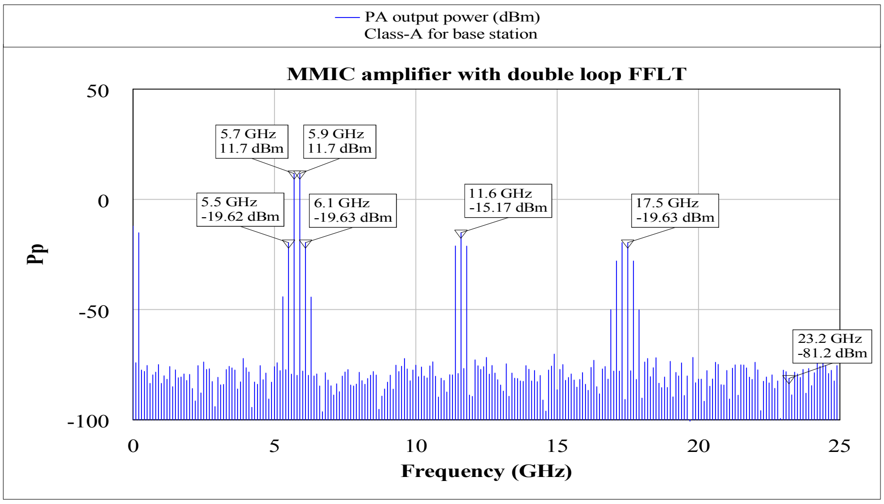

Figure 11. The two-tone test power spectrum of the main amplifier in the proposed double loop FFLT with input power level of -3.98 dBm.

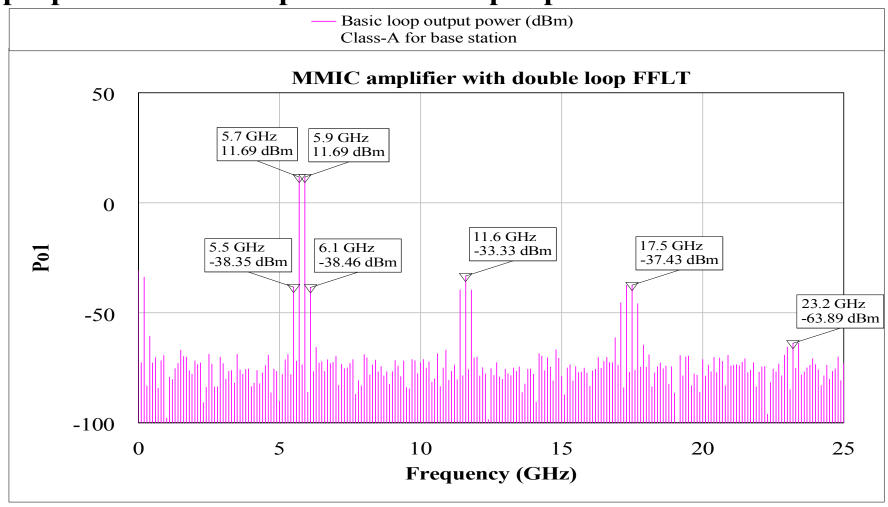

Figure 12. The two-tone test power spectrum of the basic loop in the proposed double loop FFLT with input power level of -3.98 dBm.

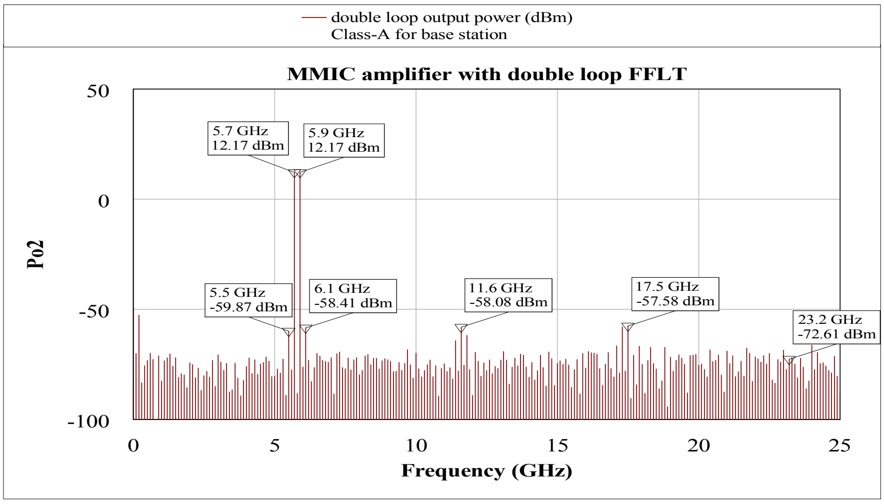

Figure 13. The two-tone test power spectrum of the second loop in the proposed double loop FFLT with input power level of -3.98 dBm.

The second two-tone test was carried out using an input power of 5.55 dBm. Figure 14, Figure 15, and Figure 16 show the output power spectrums of the main amplifier, the basic FFLT, and the double loop FFLT, respectively. Figure 14 shows a main signal power of 15.39 dBm accompanied with maximum intermodulation distortion of 2.879 dBm,Figure 15 exhibits main signal power of 21.26 dBm associated with maximum intermodulation distortion of -14.75 dBm, and Figure 16 exhibits main signal power of 21.72 dBm associated with maximum intermodulation distortion of -37.65 dBm.

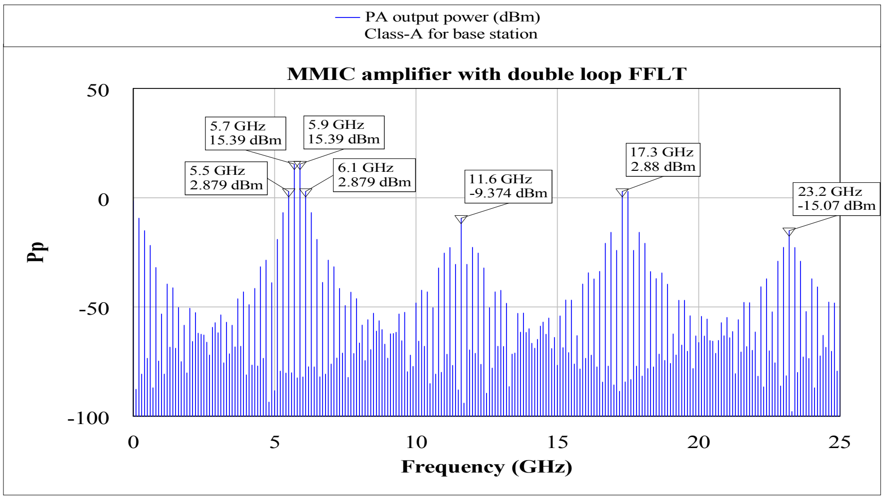

Figure 14. The two-tone test power spectrum of the main amplifier in the proposed double loop FFLT with input power level of 5.55 dBm.

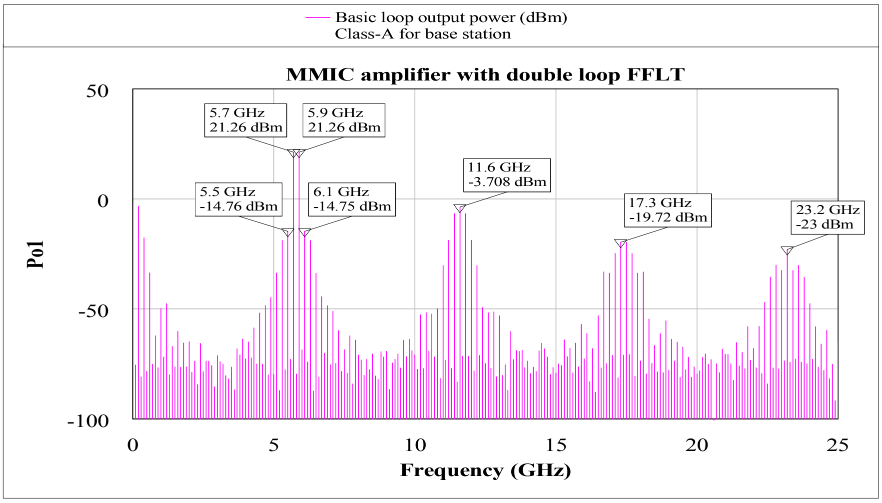

Figure 15. The two-tone test power spectrum of the basic loop in the proposed double loop FFLT with input power level of 5.55 dBm.

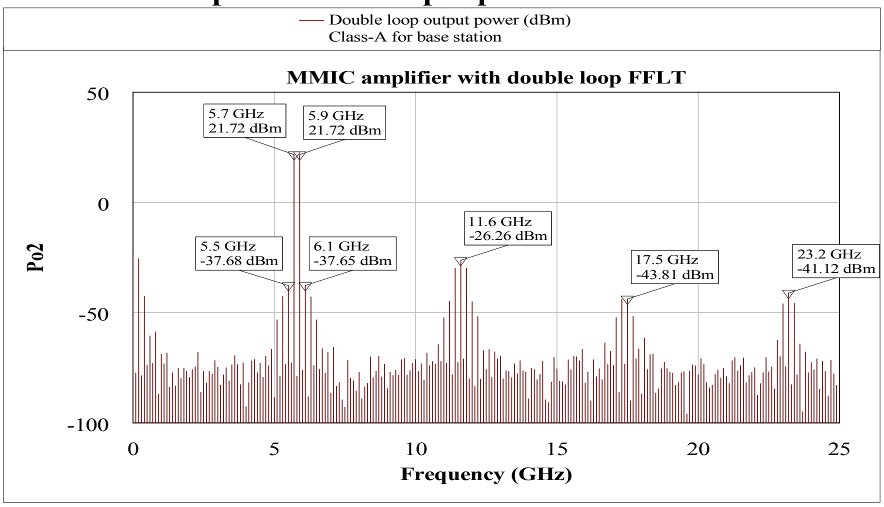

Figure 16. The two-tone test power spectrum of the second loop in the proposed double loop FFLT with input power level of 5.55 dBm.

The basic loop has contributed its maximum linearization capability in the output of the FFLT associated with significant cancellation in intermodulation distortions, while the second linearization loop has no significant linearizing contribution, but it has provided significant cancellation in the intermodulation distortions.

The third two-tone test was carried out using an input power of 7.4 dBm. Figure 17, Figure 18, and Figure 19 show the output power spectrums of the main amplifier, the basic FFLT, and the double loop FFLT, respectively. Figure 17 shows a main signal power of 15.57 dBm accompanied with maximum intermodulation distortion of 3.981 dBm, Figure 18 exhibits main signal power of 21.13 dBm associated with maximum intermodulation distortion of -8.337 dBm, and Figure 19 exhibits main signal power of 22.8 dBm associated with maximum intermodulation distortion of -18.25 dBm.

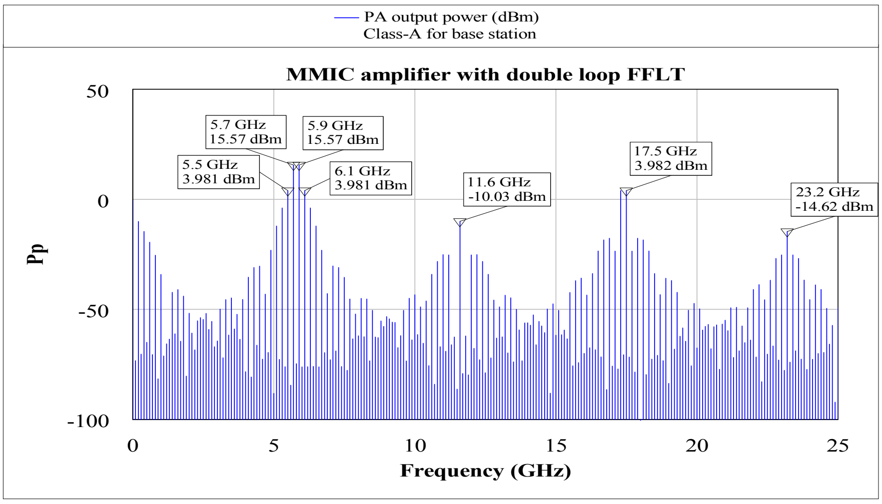

Figure 17. The two-tone test power spectrum of the main amplifier in the proposed double loop FFLT with input power level of 7.4 dBm.

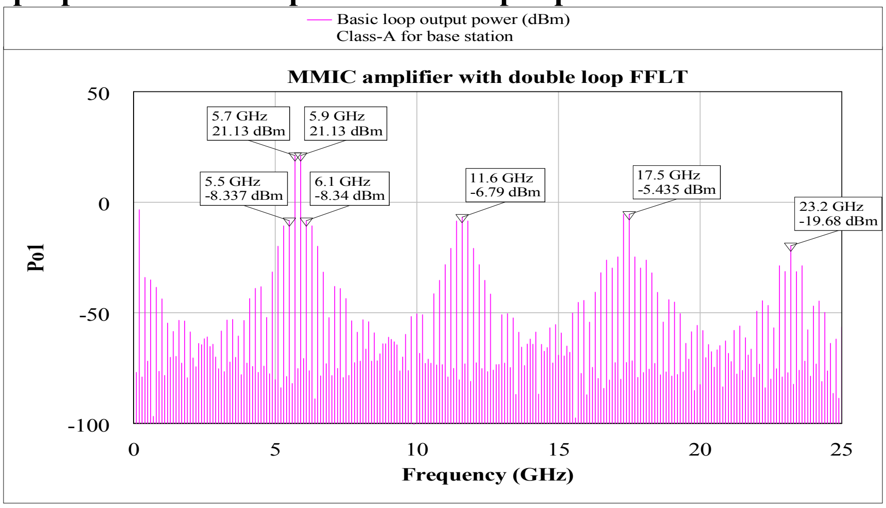

Figure 18. The two-tone test power spectrum of the basic loop in the proposed double loop FFLT with input power level of 7.4 dBm.

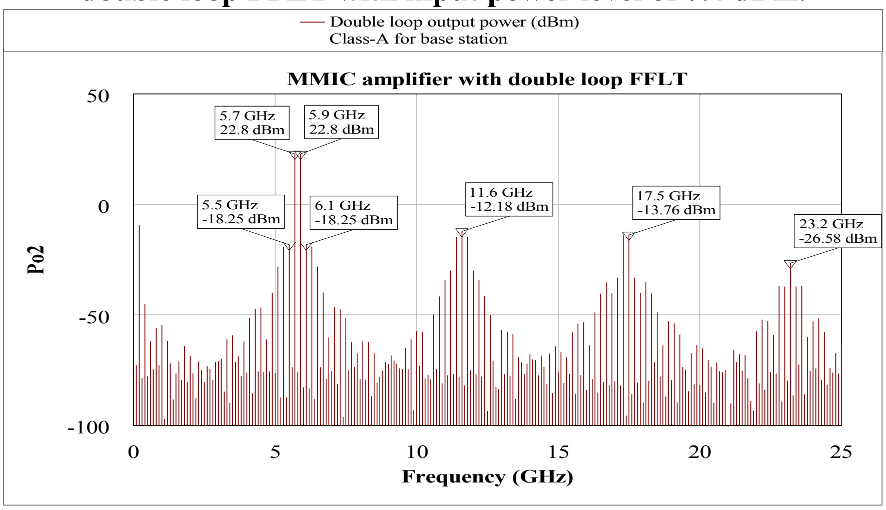

Figure 19. The two-tone test power spectrum of the second loop in the proposed double loop FFLT using class-A power amplifiers with input power level of 7.4 dBm.

Both linearization loops have contributed RF power corresponding to main signals at the output of the FFLT associated with significant cancellation in intermodulation distortions.

Figure 20 shows the IMD3 of the proposed double loop FFLT. It is obvious that both basic loop and double loop FFLTs show significant reduction in intermodulation distortion IMD3, but the double loop system reveals better performance.

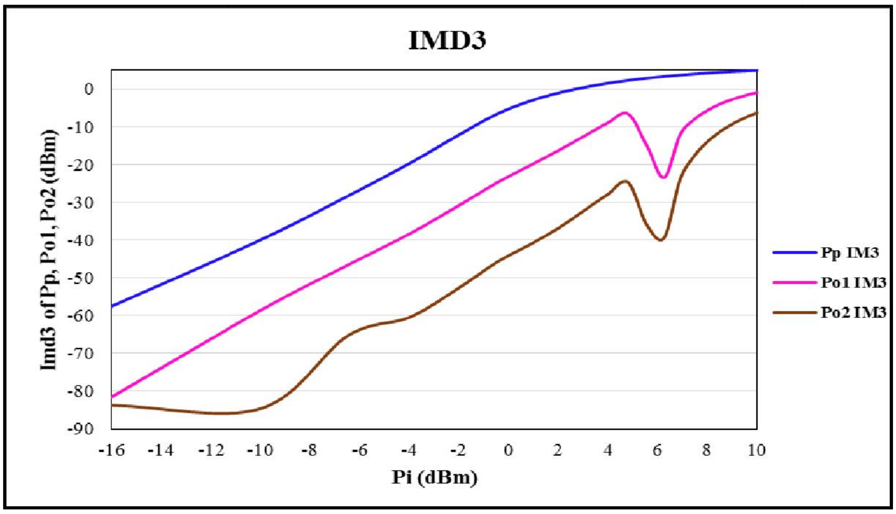

Figure 20. The IMD3 of the main amplifier, the basic loop, and double loop FFLT using class-A power amplifiers.

Moreover, the proposed double loop feedforward linearization technique was tested using an OFDM signal of an output level of 10 at a center frequency of 5.8 GHz and characterized by the following: number of subcarriers = 128, the subcarrier spacing = 1.5625 MHz, and the guard interval = 0.125.The result of this test is shown in Figure 21.

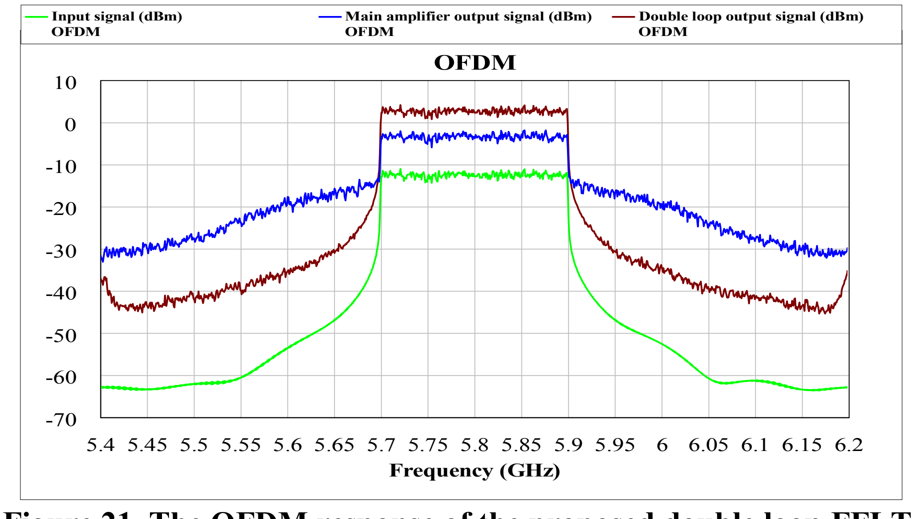

Figure 21. The OFDM response of the proposed double loop FFLT.

5. Conclusion

A 2-stages class-A power amplifieris designed with a bandwidth of 500 MHz and a gain of about 17dB.It is used as error amplifierin the proposed double loop FFLT at 5.8GHz to linearizea MMIC low noise amplifier having a gain of 16.5dB. The linear region of the MMIC amplifier stopped at 18dBm,the proposed double loop FFLThas increased its linearity by 8dBm. Also, the cancellation of the IMD3 has been improved by the proposed double loop FFLT better than the basic FFLT does.

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