Linearity Improvement of Microwave Amplifiers by Special Harmonic Loads

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ABSTRACT
In this paper, the effects of special harmonic loads are presented in the case of microwave amplifiers. The third-order intercept point (IP3) and the 1-dB compression point (P1dB) of the amplifier are improved with the use of special harmonic loads. To demonstrate this effect an amplifier was designed applying a BFG424F NPN type bipolar transistor. The amplifier was designed for a broad band providing gain from 1 GHz to 6 GHz. This way it can be used for testing its performance with the harmonic loads. The effect of loads is demonstrated for a 1.5 GHz sinusoidal signal. Two cases will be shown in this paper. In the first case the harmonic load was designed to reflect the 3 GHz component (the 2nd harmonic of the input signal) in opposite phase back to the amplifier, while in the second case the 4.5 GHz component (the 3rd harmonic of the input signal) is reflected. With the use of this load the gain at 1.5 GHz is improved by 2 dB and the third-order input intercept point is also improved by 1 dB. A significant advantage of the present approach is that the delay time of the harmonic reflection is very short which means a large bandwidth.
Keywords: microwave amplifier; harmonic load; third-order intercept point; 1-dB compression point

1. INTRODUCTION

In most of the radio frequency (RF) applications it is important that the devices (e.g. the amplifiers) have to operate in the linear range. Therefore, the investigation of the linear operating range is a crucial problem. The linearity of a device can be characterized by the intermodulation product. For this purpose the third-order intercept point (IP3 or TOI) is used. The IP3 of a microwave amplifier can be improved by increasing the collector current, using a series capacitance decoupling the base to the ground or using feedforward distortion cancellation (FDC) method [1]. In this paper we show a method to increase the IP3 by using harmonic load at the output of the amplifier. Simulation and measurement results show that this method also increases the gain and the linear operating range of the amplifier.

2. DESIGN AND SIMULATION OF THE AMPLIFIERS

2.1 Simulation of the amplifier without harmonic load

To demonstrate the effect of the harmonic load an amplifier is designed with maximum gain at 2 GHz. First an active element, which is unconditionally stable, has to be chosen for the amplifier. The stability of a two port network can be determined by the scattering parameters of the network. Equation (1) and (2) show the condition of the unconditional stability with the use of the Rollett factor (K) and the determinant (Δ) of the scattering parameters [2]:

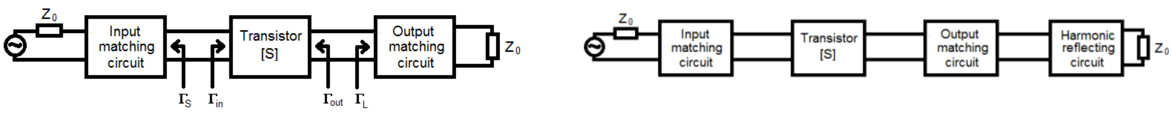
$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2 \cdot |S_{12} \cdot S_{21}|} > 1 \qquad (1)$$

$$|\Delta| = |S_{11} \cdot S_{22} - S_{12} \cdot S_{21}| < 1 \qquad (2)$$

In the case of the chosen transistor these conditions are satisfied above 1.3 GHz in the case of 30 mA collector current and 4 V collector-emitter voltage. The block diagram of the amplifier is shown in Fig. 1a. The block in the middle contains the transistor (the Gummel-Poon model in our case), the bias network, the coupling capacitors and the RF chokes. This block is unconditionally stable in the simulated 1–4 GHz frequency range.

The input and the output matching circuits are designed to reach maximum gain at 2 GHz. Maximum power transfer from the input matching circuit to the transistor will occur when the input reflection coefficient of the transistor (Γ_{in}) and the reflection coefficient at the output of the input matching circuit (Γ_S) are conjugate matched to each other.

$$\Gamma_{in} = \Gamma_S^* \qquad (3)$$



a) b)

Figure 1. Block diagram of the amplifier with (a) and without (b) harmonic reflecting circuit.

Similarly for the output the maximum power transfer will occur when

$$\Gamma_{out} = \Gamma_L^* \tag{4}$$

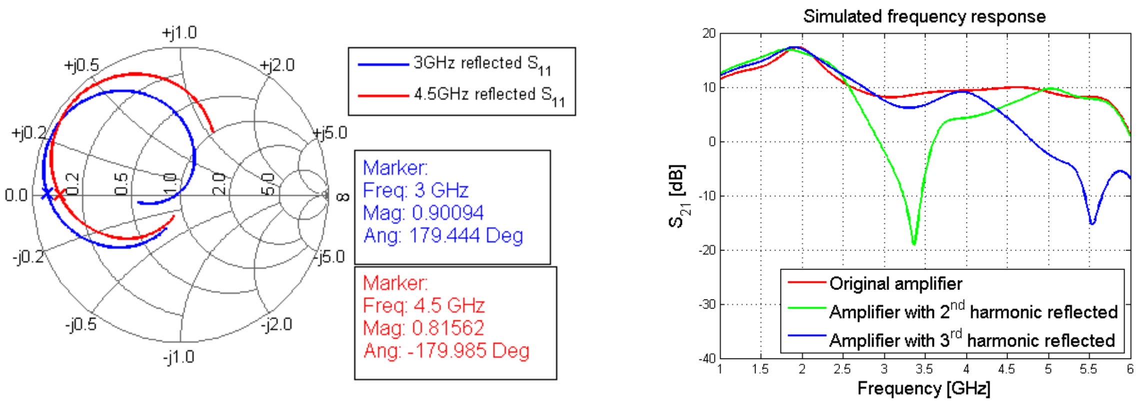
From (3) and (4) the required source (Γ_S) and load (Γ_L) reflection coefficient can be calculated. In our case these impedance matching circuits are designed for 2 GHz in the case of FR4 substrate with thickness of 8 mm.

2.2 Simulation of the amplifier with harmonic load

AWR Microwave Office is used to simulate the amplifier and the harmonic loads. The block diagram of the amplifier with harmonic load can be seen in Fig. 1b. In this case, a block is inserted between the output matching circuit and the load impedance. This harmonic reflecting block is a single-stub matching network which uses the 50 Ω load impedance to synthesize an impedance which reflects back the 2nd or the 3rd harmonic of the 1.5 GHz sinusoidal signal. Fig. 2a shows the input impedance of each harmonic reflecting circuit. The blue curve shows the input impedance of the harmonic reflecting circuit which reflects the 2nd harmonic. The marker shows that the impedance at 3 GHz is almost real and the value of it is 2.6 Ω. It means that the phase of the reflected signal is 180° and the magnitude of the reflection coefficient is about 0.9. In the figure we can see that the magnitude of the reflection coefficient is larger at 3.5 GHz than at 3 GHz but the phase is lower than 180°. The other curve shows the impedance of the other harmonic reflecting circuit, which reflects the 3rd harmonic. In this case the value of the input impedance at the 3rd harmonic (4.5 GHz) is about 5 Ω so the magnitude of the reflection coefficient is about 0.82 and the phase is 180°.

2.3 Simulation results

The three amplifiers are compared by the frequency response, the IP3 and the 1-dB compression point (P1dB). Fig. 2b shows the simulated frequency response of the amplifiers from 1 GHz to 6 GHz. The effect of the reflection can be seen at 3–3.5 GHz and 4.5–5.5 GHz. In this figure also it can be seen that the largest reflections belong to higher frequencies than the 2nd and the 3rd harmonic. If we have a look at the gain between 1 and 2 GHz we can see the other effect of the reflection circuit. The gain is larger in the case when the 2nd (green curve) or the 3rd (blue curve) harmonic is reflected than in the case of the original amplifier (red curve). Table 1 summarizes the simulated parameters of each amplifier at 1.5 GHz. The gain is in the first column of the parameters. It shows that the gain is 1.8 dB larger in the case when the 2nd harmonic reflected and 1.1 dB larger when the 3rd harmonic is reflected compared to the gain of the original amplifier. It can be seen that all other parameters are better in the case when a harmonic reflecting circuit is used. In the case when the 2nd or the 3rd harmonic is reflected P1dB is 0.7 or 0.3 dB larger, input intercept point (IIP3) is 1 or 0.5 dB larger and the output intercept point (OIP3) is 2.9 or 1.6 dB larger than the values of the original amplifier, respectively. The parameters of the IP3 are simulated with two tones at 1 GHz with 1 MHz spacing.



a) b)

Figure 2. (a) The simulated input impedance of the harmonic loads and (b) the simulated frequency response of the amplifiers.

Table 1. The simulated parameters of the amplifiers

Amplifiers	Parameters at 1.5 GHz			
	Gain [dB]	*P1dB [dBm]*	*IIP3 [dBm]*	*OIP3 [dBm]*
Original	13.7	–7	2.3	15.9
2nd harmonic reflected	15.5	–6.3	3.3	18.8
3rd harmonic reflected	14.7	–6.7	2.8	17.5

Table 2. The measured parameters of the amplifiers

Amplifiers	Parameters at 1.5 GHz			
	Gain [dB]	*P1dB [dBm]*	*IIP3 [dBm]*	*OIP3 [dBm]*
Original	11.6	–9.5	4.5	15.7
2nd harmonic reflected	13.6	–8	7.5	20.7
3rd harmonic reflected	13.4	–9	6.9	19.9

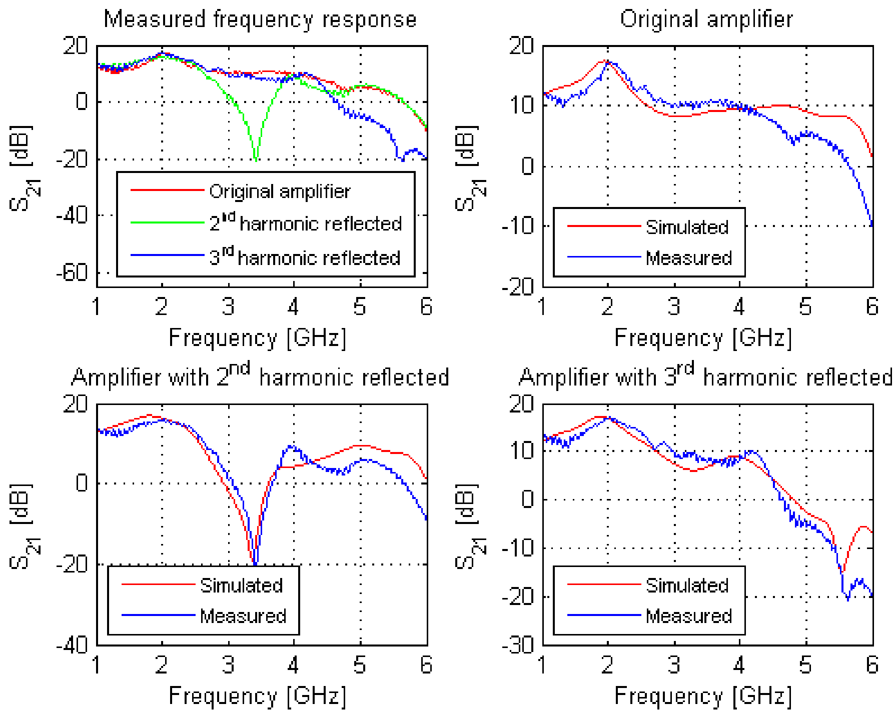
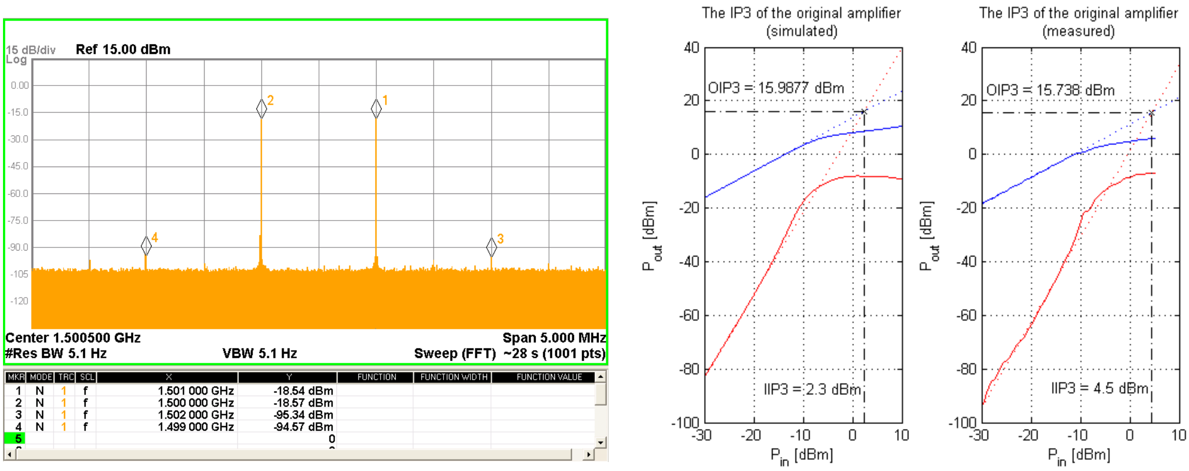


Figure 3. Measured frequency response of the amplifiers.

3. MEASUREMENT RESULTS

The three amplifiers were manufactured on FR4 substrate. Although FR4 substrate is not optimal for microwave frequencies it was chosen for the purpose of demonstrating the effect of the special harmonic reflecting loads using a commonly used substrate. Fig. 3 shows the frequency responses of the amplifiers. The first diagram shows the responses like Fig. 2b in the case of the simulation. The effects of the reflection circuits can also be observed in this diagram. The gain between 1 and 2 GHz is larger in the case when harmonic reflecting circuit is used. The other diagrams compare the simulation (red curve) and the measurement (blue curve) results for each amplifier. These diagrams show that the measurement results are close to the simulation results.

The gain at 1.5 GHz is 11.6 dB in the case of the original amplifier, 13.6 dB or 13.3 dB in the case when the 2^{nd} or 3^{rd} harmonic is reflected, respectively. These values are 2 dB lower than the simulated ones but the effects of the harmonic reflecting circuits are quite the same. The gains are 2 dB or 1.8 dB larger than the gain of the original amplifier while in the simulation the gains are 1.8 dB or 1 dB larger, respectively. Table 2 summarizes the measured parameters of the amplifiers at 1.5 GHz. The P1dB is in the second column of the parameters. These values are 2 dB lower than the values in the simulation as in the case of the gain. Here we can see that the values are 1.5 or 0.5 dB larger than the value of the original amplifier in the case when the 2^{nd} or the 3^{rd} harmonic is reflected, respectively. The linearity of the amplifiers is characterized by a two-tone test. For this setup, the result of the test is shown in Fig. 4a in the case of the original amplifier at 1.5 GHz with 1 MHz spacing and –30 dBm input power for each tones. A complete IP3 characterization curve is shown in Fig. 4b. The simulation result is shown in the left diagram while the measurement result is in the right one. The blue curve shows the power of the fundamental signal and the red curve shows the power of the third-order intermodulation distortion. The measured output power of the fundamental signal is close to the simulated one.



a) b)

Figure 4. (a) Two-tone test for the original amplifier with input power of –30 dBm at 1.5 GHz with 1 MHz spacing and (b) the simulated and measured IP3 of the original amplifier. The blue curve shows the power of the fundamental signal and the red curve shows the power of the third-order intermodulation signal

The measured power of the intermodulation distortion is better than the simulated in the case of low input power and close to the simulation in the saturation region. We can see that the IIP3 from the measurement 2 dB larger than the simulated value while the OIP3 is close to the simulation. Table 2 contains the IIP3 and OIP3 parameters of the other amplifiers. The measurement results show, similarly to the simulation, that the IIP3 of the amplifier with harmonic load is larger than the original amplifier. These results show that the harmonic loads have larger effect on this parameter. The IIP3 is 3 or 2.4 dB larger than the IIP3 of the original amplifier in the case when the 2nd or the 3rd harmonic is reflected, respectively. Similar effect can be seen in the OIP3 parameter of the amplifiers but the difference is 5 or 4 dB from the value of the original amplifier in the two cases.

4. CONCLUSIONS

In this paper we presented the simulation of a microwave amplifier and the effect of harmonic loads on the frequency response, the IP3 and the P1dB of the amplifier. We demonstrated that harmonic terminations have an effect on amplifier parameters. Further investigation is necessary to find harmonic terminations resulting in optimum amplifier parameters. Two cases of the harmonic loads are shown. The first reflected back the 3 GHz (2nd harmonic of the used input signal) component in opposite phase to the output of the amplifier while in the second case the 4.5 GHz (3rd harmonic) is reflected in opposite phase. These loads improved the gain of the amplifier by 1.8 or 1 dB in the case when the 2nd or the 3rd harmonic is reflected. Similarly the P1dB and the IIP3 are improved by 0.3–0.7 dB and 0.5–1 dB, respectively. The simulation results have been verified by measurements and show that the gain, P1dB and IIP3 are improved by 1.8–2 dB, 0.5–1.5 dB and 2.4–3 dB, respectively.

ACKNOWLEDGEMENTS

This work was supported by the Ericsson Hungary Ltd. Authors are grateful to Dr. János Ladvánszky of the Ericsson R&D Hungary for his kind encouragement and internal revision.

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