Performance Enhancement of Doherty Power Amplifier with LINC

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Abstract: In this paper, we analysis doherty amplifier's electric nonlinearity and electrothermal memory effect and propose a proper compensator structure, LINC(LInear amplification using Nonlinear Components), with W-CDMA signal input. A power amplifier is important component that decide efficiency in communication system. A doherty power amplifier is good efficiency. However, it has high distortion characteristic. For high efficiency and linearity, we propose a proper doherty amplifier sheme with temperature compensation. The ACLR characteristics of compensated doherty amplifier is improved 12.55 dB at 5 MHz offset frequency.

1. Introduction

In broad-band base-station RF amplifier demands more high efficiency and high linearity than general RF amplifier. A proper design for RF amplifier is getting more and more difficult. It is complex than various RF amplifier compensators satisfy various distortions. Doherty amplifier is high efficiency than general balanced amplifier. The doherty amplifier's characteristics are restricted by insufficient factors for doherty amplifier design process, though [1][2]. The insufficient factors change by power device types and structures. A general designs focus only amplitude distortions and phase distortions. Recently, a memory effect and linearity are very important factors. The key-point is proper structure and exact memory effect analysis for high efficiency and high power doherty amplifier.

The general structure of doherty amplifier has a weak point which undergoes high distortion such as 3rd IMD(inter-modulation distortion) and 5th IMD distortion. The distortion result from a sudden variation of impedance at signal synthesized point. To reduce distortion by structure of doherty amplifier, it demands complex compensator. The memory effect is defined electric memory effect and electrothermal memory effect. The electric memory effect is occurred by bias and matching circuit's impedance variation in baseband and harmonics band. Especially, bias and matching circuit design is important in FET power amplifier. And the electrothermal memory effect is FET power amplifier's gain variation by transistor temperature. The electrothermal memory effect is inevitable factor [3].

Therefore, we analysis doherty amplifier's electric nonlinearity and electrothermal memory effect and propose a proper compensator structure, LINC(LInear amplification using Nonlinear Components).

2. Basics of doherty amplifier and LINC

Doherty amplifier, first proposed in 1936, is primarily an efficiency enhancement or power conservation technique[4]. The general doherty amplifier's concept is that the resistance or reactance of an RF load can be modified by applying current from a second, phase-coherent source with common load. And it is important that the quarter-wave transformer between the common load resistor and the main device output. This acts as an impedance inverter, which causes the resistive impedance seen by the main device to go down as the auxiliary device current increases. A real doherty amplifier has a problem. The quarter-wave transformer changes impedance by power level. The impedance variation cause mismatching and then, such mismatching cause many of distortions. Therefore, doherty amplifier's efficiency is dropped [5][6][7].

The Linear amplification using Nonlinear Components (LINC) technique was first proposed by Cox in 1974 [8] as a method of achieving linear amplification at microwave frequencies-a feat which was virtually impossible at the time due to the lack of suitable linear devices at microwave frequencies. The basic scheme of a LINC for amplifier is shown in figure 1, where the two RF amplifiers are assumed to be high-efficiency and highly nonlinear. The RF input signal, $V_{in}(t)$, is split into two constant envelope, phase modulated signals by the signal separation or generation process, and each is fed to its own nonlinear RF power amplifier. The power amplifiers separately increase the power of each signal by an identical amount, before feeding them to an ideal summing junction for recombination. The resulting output signal from the summing junction is then an amplified version of the original input signal with no added distortion.

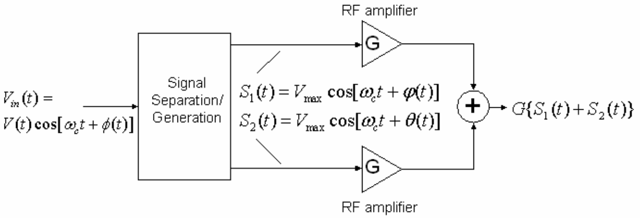

Figure 1. A basic scheme of LINC for amplifier.

The input signal, $S(t)$, is given by equation (1).

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$$S(t) = V(t)\cos[\omega_c t + \phi(t)] \tag{1}$$

where $V(t)$ is the amplitude modulation present on the signal, ω_C is the carrier frequency and $\phi(t)$ is the phase-modulation component of the signal. The input signal is split into two constant-envelope phase modulated signals, $S_1(t)$ and $S_2(t)$ where,

$$S_1(t) = V_{\max}\cos[\omega_c t + \varphi(t)] \tag{2}$$

$$S_2(t) = V_{\max}\cos[\omega_c t + \theta(t)] \tag{3}$$

where, $\varphi(t) = \phi(t) + \alpha(t)$ and $\theta(t) = \phi(t) - \alpha(t)$.

For these signals to recombine and produce the correct linearly amplified version of the input signal, the following relationships must also hold.

$$\begin{aligned} 2S(t) &= S_1(t) + S_2(t) \\ \alpha(t) &= \cos^{-1}[V(t)/V_{\max}] \end{aligned} \tag{4}$$

Thus, the above signals, $S_1(t)$ and $S_2(t)$, must be successfully and accurately generated in order for the benefits of the LINC technique to be realized. If the input signal is provided in quadrature form as equation (5).

$$S(t) = s_I(t) + s_Q(t) \tag{5}$$

Then the two LINC component signals may be defined as equation (6).

$$\begin{aligned} s_1(t) &= s(t) + e(t) \\ s_2(t) &= s(t) - e(t) \end{aligned} \tag{6}$$

where, $e = -s_Q(t)\sqrt{\dfrac{1}{(s_I^2(t) + s_Q^2(t))} - 1} + js_I(t)\sqrt{\dfrac{1}{(s_I^2(t) + s_Q^2(t))} - 1}$.

3. Characteristics of electrothermal memory effect

A transistor junction temperature analysis is important for the characteristics of electrothermal memory effect. A transistor junction temperature is (7) that has thermal impedance and dissipated power in envelope frequency.

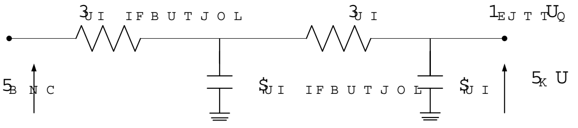
$$T_j = T_{amb} + R_{th} * P_{dissip}(DC) + Z_{in}(\omega_1 - \omega_2) * P_{dissip}(\omega_1 - \omega_2) \tag{7}$$

The dissipated power is determined by the instantaneous thermal ratio at envelope frequency. The thermal impedance includes a capacitance in addition to the resistance due to restricted transistor's physical size. A thermal resistance describes steady-state, and thermal capacitance describes dynamic state[9]-[11]. The thermal resistance and capacitance is similar RC constant in electric resistance and capacitance. The relation of instantaneous junction temperature in transistor has duality between thermal transmission and electric phenomena and describes in table 1.

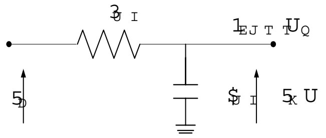
A figure 2 shows thermal model of transistor. The figure 2(a) was simplified to (b) since thermal constant $R_{\text{th,heatsink}} \times C_{\text{th,heatsink}}$ is too larger than electric constant $R_{\text{th}} \times C_{\text{th}}$.

Table 1. Thermal and electrical quantities equivalence

Parameter	Thermal Quantity		Electrical Quantity
P_{dissp}	Dissipated Power(W)	I	Current(A)
T_j	Temperature(K)	V	Voltage(V)
R_{th}	Thermal Resistance(K/W)	R	Electrical Resistance(Ω)
C_{th}	Thermal Capacitance(J/K)	C	Electrical Capacitance(F)



(a) A thermal model



(b) A simplified thermal model

Figure 2. A transistor thermal model.

The instantaneous temperature can be expressed as a solution to the following first-order nonhomogeneous differential equation (8).

$$\frac{\partial T_j(t)}{\partial t} + \frac{1}{R_{th}C_{th}} T_j(t) = \frac{1}{R_{th}C_{th}}(R_{th}P_{dissip}(t) + T_c) \tag{8}$$

where, $P_{dissip}(t) = V_{DS,dc}(t) \times I_{DS,dc}(t) + P_{RF,in}(t) - P_{RF,out}(t)$ (9)

$$P_{dissip}(t) = (1 - \eta(t)) \times P_{RF,out}(t) \tag{10}$$

and $\eta(t)$ is instantaneous power efficiency.

Equation (8) has the form (11).

$$\frac{\partial}{\partial t}T_j(t) + a(t)T_j(t) = b(t) \tag{11}$$

where $a(t) = \dfrac{1}{R_{th}C_{th}}$, $b(t) = \dfrac{1}{R_{th}C_{th}}(R_{th}P_{dissip}(t) + T_c)$.

The general solution of (11) is (12).

$$T_j(t) = e^{(-\int a(t)dt)}\left(\int e^{(-\int a(t)dt)} b(t)dt + K\right) \tag{12}$$

This equation is equivalent to (13).

$$T_j(t) = e^{-t/\tau}\left(\int \frac{1}{\tau} e^{t/\tau}(R_{th}P_{dissip}(t) + T_c)dt + K\right) \tag{13}$$

where $R_{th}C_{th} = \tau$ is the thermal time constant.

The integral on the right-hand-side expression of (13) can be rewritten as (14).

$$T_j(t) = e^{1/\tau}\left\{\int \frac{\partial e^{(1/\tau)}(R_{th}P_{dissip}(t) + T_c)}{\partial t} dt - \int R_{th}e^{(1/\tau)}\frac{\partial p_{dissip(t)}}{\partial t} dt + K\right\} \tag{14}$$

In the particular case, the instantaneous power is constant at step input signal excitation and then, the instantaneous dissipated power also remains constant. Therefore, instantaneous dissipated power can write (15).

$$P_{dissip}(t) = \left\{ \begin{matrix} P & t_0 \le t \le T \\ P_0 & t \le t_0 \end{matrix} ; \frac{\partial P_{dissip}(T)}{\partial t} = 0 \right\} \qquad (15)$$

$$with \tau <> T$$

Equation (16) is rewritten (14) from (15).

$$T_j(t) = T_{j,s} + (T_{j,0} - T_{j,s}) \times e^{-\Delta t/\tau} \qquad (16)$$

where $T_{j,0} = T_c + R_{th} P_0$ and $T_{j,s} = T_c + R_{th} P$.

Figure 4 shows output signal with respect to the junction temperature variation with input signal, shown in a figure 3.

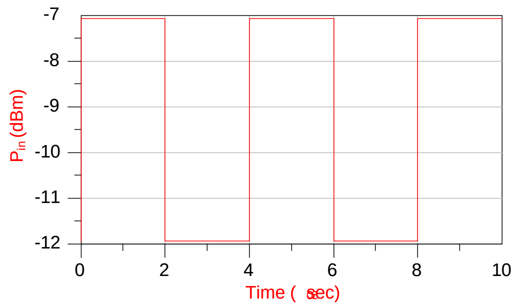


Figure 3. Input pulsed signal envelope(period 4 œs, duty cycle =0.5).

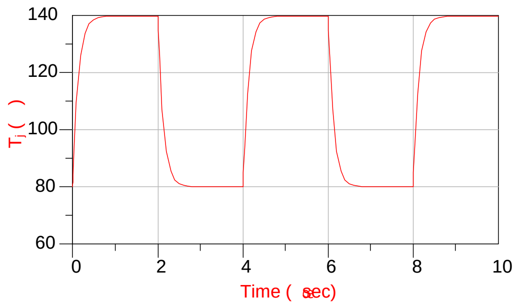


Figure 4. Junction temperature variation versus time for signal (period 4 œs, duty cycle =0.5).

4. Design of compensated LINC for doherty amplifier

We design a temperature compensator for LINC from electrothermal model of doherty amplifier. A figure 5 shows doherty amplifier and LINC which has temperature compensator. The function f(!) and g(!) are complex models of memory-less nonlinearity; AM-AM and AM-PM.

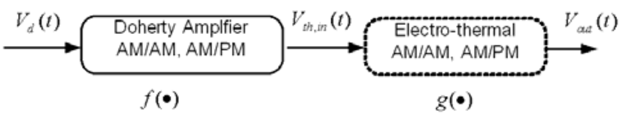


Figure 5. A scheme of doherty amplifier model.

Figure 6 and 7 show gain compression and phase shift with respect to junction temperature of doherty amplifier.

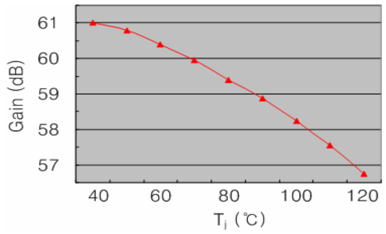


Figure 6. Gain compression versus junction temperature of doherty amplifier.

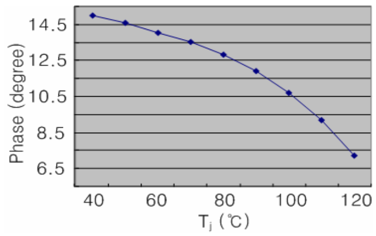


Figure 7. Phase shift versus junction temperature of doherty amplifier.

The characteristics of doherty amplifier are measured results under small signal regions. The gain compression characteristic of doherty amplifier is related not electrical nonlinearity but variation of junction temperature. Figure 8 shows dissipated drain current for each temperature. In this figure, we observe that instantaneous junction temperature and dissipated power doherty amplifier model derive from dissipated drain current.

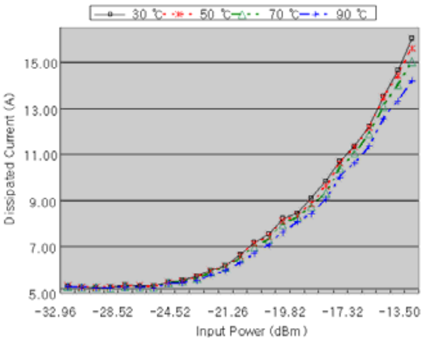


Figure 8. Pulse measurements of the drain current versus input level.

Figure 9 shows simulated output envelope signal of doherty amplifier under test which is exited rectangular signal with 50% duty cycle. The output envelope signal varies exponential increment and decrement by junction temperature exponential variation.

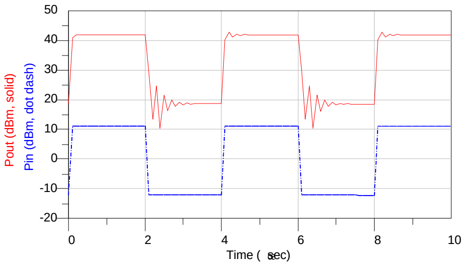


Figure 9 Simulated output envelope signal (Period 4 k, Duty cycle 50%).

The junction temperature of transistor depends on instantaneous dissipated power and variation of input signal. The complex characteristics of doherty amplifier depend on junction temperature, hence it look on nonlinearity factor.

Figure 10 shows temperature compensated LINC for doherty amplifier. The cascade of doherty amplifier and temperature compensated LINC.

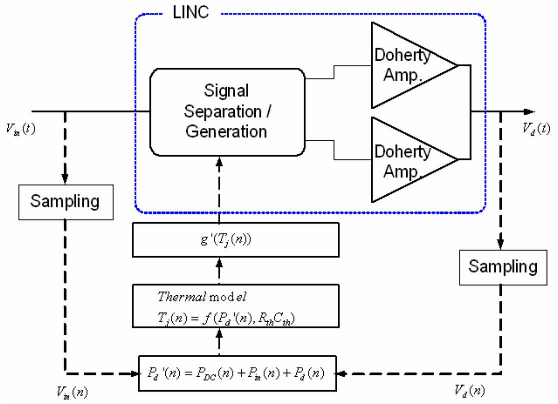


Figure 10. A scheme of temperature compensated LINC.

The performance of doherty amplifier with temperature compensated LINC is measured by W-CDMA signal. The W-CDMA signal was synthesized by ADS library. The center frequency is 2.14 GHz and the symbol rate is 3.6864 MHz.

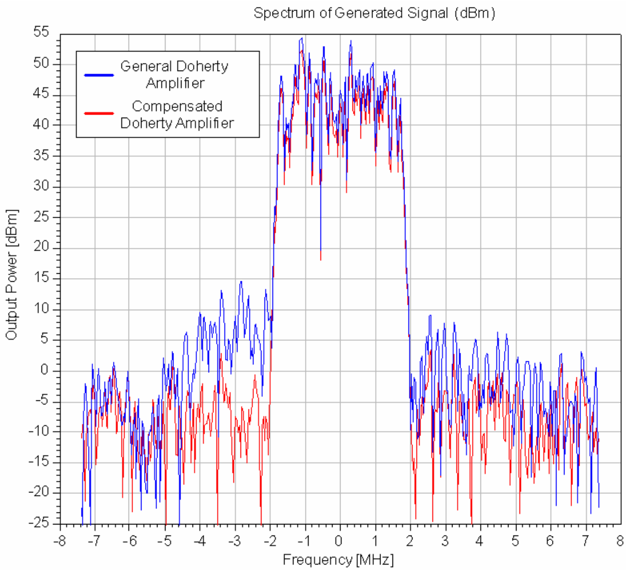


Figure 11. A output spectrum of doherty amplifier with temperature compensated LINC.

Figure 11 shows output spectrums of doherty amplifier with temperature compensated LINC and general doherty amplifier. In general doherty amplifier, output power is 45.75 dBm and ACLR characteristics is -36.84 dBc and -45.38 dBc at 3 MHz and 5 MHz offset frequency. In compensated doherty amplifier, output power is 45.62 dBm and ACLR characteristics is -53.24 dBc and -57.93 dBc at 3 MHz and 5 MHz offset frequency. The output characteristic of compensated doherty amplifier is better than general doherty amplifier. Output power is decreased 0.13 dB and ACLR characteristics is reduced 16.40 dB and 12.55 dB at 3 MHz and 5 MHz offset frequency. Therefore, the doherty amplifier with temperature compensated LINC is maintained output power and is enhanced linearity.

5. Conclusions

In this paper, we proposed a doherty amplifier with temperature compensated LINC which is good linearity. A doherty amplifier with temperature compensated LINC enhance characteristics of ACLR that input signal split temperature compensated amplitude and temperature compensated phase information and then signal of each path is amplified by high efficiency doherty amplifier. The ACLR characteristics of compensated doherty amplifier is improved 12.55 dB at 5 MHz offset frequency. In a future work, we will study on implementation of electrothermal compensated LLHD amplifier.

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