DESIGN OF WIDEBAND LTE POWER AMPLIFIER WITH NOVEL DUAL STAGE LINEARIZER FOR MOBILE WIRELESS COMMUNICATION

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Received 16 January 2013
Accepted 17 April 2014
Published 21 May 2014

In this paper, a 1 mm × 1 mm fully integrated wideband dual-stage power amplifier (PA) for long-term evolution (LTE) band 1 (1920–1980 MHz) is presented. Fabricated in a 2 μm InGaP/GaAs hetero-junction bipolar transistor (HBT) process, the operating gain is observed to be 31.3 dB. The PA meets the minimum adjacent channel leakage ratio (ACLR) requirement of ≤30 dBc for LTE with 20 MHz wide channel bandwidth up to an output power of 30 dBm with the aid of a novel dual stage linearizer. Biased at low quiescent current of less than 100 mA with a headroom consumption of 3.5 V, the power added efficiency (PAE) is observed to be 38.29% at 30 dBm. With this high linear output power, the stringent requirement of antenna path loss is nullified. PA serves to be the first reported work to achieve 30 dBm linear output power at supply voltage of 3.5 V.

Keywords: Power amplifier; linearizer; LTE.

1. Introduction

The demand for high data rate information in modern wireless communication systems has led to the birth of long-term evolution (LTE). LTE presents great opportunities for high speed wireless communication. However, the requirement of high output data rate results in an increased signal complexity such as the employment of multicarrier modulation standards and non-constant envelope modulation techniques. LTE employs quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) modulation techniques. The access
scheme used by LTE is single carrier frequency division multiple access (SC-FDMA) which is subjects it to peak to average power ratio (PAPR) issue. PAPR limits the true capacity of the signal due to distortion caused by the nonlinear characteristics of the power amplifier (PA).\textsuperscript{1} In reference to this signal complexity, the transmitter system, especially the PA needs to maintain a linear operating region. A conventional method is to operate the PA at a prescribed back-off region from the maximum output power.\textsuperscript{2} Although it ensures linear operation, power added efficiency (PAE) is gravely sacrificed. The linearity performance of a LTE PA is characterized by the adjacent channel leakage ratio (ACLR) requirement. In reference to the ETSI 3GPP specification (TS36.101 release 10), the PA needs to meet a minimum requirement of $-30$ dBc in ACLR to ensure a linear transmission.

Initial research efforts focus in improving the efficiency of the linear PA for 10 MHz LTE channel bandwidth, where the efficiency obtained is reported to be more than 30%.\textsuperscript{3,4} Thereafter, the envelope tracking method begins to gain its popularity in improving the efficiency and bandwidth of a linear PA. In this method, the PA is able to transmit linearly for LTE channel bandwidth more than 10 MHz, which is up to 20 MHz\textsuperscript{5} and 30 MHz.\textsuperscript{6} The penalty paid is reflected in the complexity of the integrated structure and high supply voltage headroom.

Instead, our proposed work focuses in improving the linearity of an efficient nonlinear PA. The third-order intermodulation (IMD3) cancellation technique has been explored in achieving this goal. Previous works has focused on the cascode methodology to generate IMD3 cancellation between the common source and common gate amplifier.\textsuperscript{7,8} The biasing circuit has also been utilized to cancel out the IMD3 components generated by the nonlinear main amplifier.\textsuperscript{9,10} However linear bandwidth achieved through the cascode and biasing circuit techniques is quite narrow. Therefore in extending the linear bandwidth which is a critical performance metric for LTE, a dual stage linearizer is proposed. The first stage eliminates the low frequency IMD3 components generated by the driver amplifier, preventing the bias modulation effect. Subsequently the second stage of the proposed network produces an opposite IMD3 Product to cancel out IMD3 generated by the nonlinear main amplifier. This integration results in an ACLR performance confirming to the regulated specification for LTE signal with 20 MHz channel bandwidth. With this linearization scheme in hand, the PA can be operated at a low quiescent current to maintain a favorable efficiency while transmitting linearly for a wideband LTE channel. The proposed PA operates from 1.92–1.98 GHz, encapsulating LTE band 1.

2. Principle of Operation

The conventional technique by merely reducing the supply voltage of the PA in order to operate efficiently results in gain expansion. Severe gain expansion affects the linear transmission of the PA. This is due to the rise of the IMD3 distortion component, which in turn significantly degrades the ACLR.\textsuperscript{11} Integration of an analog
pre-distorter (APD) at the input of the nonlinear PA, as shown in Fig. 1 can mitigate
this adverse effect. The APD architecture is integrated to produce IMD3 components,
which are equal in amplitude but 180° out-of-phase respective to the IMD3
spurs generated by the main amplifier. Thus, the IMD3 cancellation attained extends
the overall linear output power span of the PA. The operation in Fig. 1 can be
explained with the aid of the following analysis.

From the expression of the power series, given by:

\[
f(x) = \sum_{n=0}^{\infty} a_n x^n,
\]

\[
v_{out} = a_0 + a_1 v_{APD} + a_2 v_{APD}^2 + a_3 v_{APD}^3,
\]

\[
v_{APD} = b_0 + b_1 v_{in} + b_2 v_{in}^2 + b_3 v_{in}^3.
\]

Taking into consideration the fundamental and third-order components only and
incorporating (3) into (2):

\[
v_{out} = a_1 \left[ b_1 v_{in} + b_3 v_{in}^3 \right] + a_3 \left[ b_1 v_{in} + b_3 v_{in}^3 \right]^3
\]

\[
= a_1 b_1 v_{in} + [a_1 b_3 + a_3 b_1^3] v_{in}^3 + 3a_3 b_1^2 b_3 v_{in}^5 + 3a_3 b_1 b_3^2 v_{in}^7 + a_3 b_3^3 v_{in}^9
\]

(4)

to nullify the third-order interaction components,

\[
a_1 b_3 + a_3 b_1^3 = 0,
\]

\[
b_3 = \frac{-a_3 b_1^3}{a_1},
\]

(6)

normalizing (6) in the context of the linear fundamental gain, \(a_1/b_1^3\), establishes

\[
b_3 = -a_3.
\]

(7)

It can be concluded from (7) that in order to achieve IMD3 cancellation, the third-
order components generated at the output of the APD requires to be in an opposite
response respective to the third-order components generated by the main amplifier.
In practice, this can be achieved if an opposite AM–AM response is generated between the APD and main amplifier.\textsuperscript{12}

3. Design Methodology

Figure 2 illustrates the schematic of the proposed PA consists of an integrated APD block connected to the input of the main amplifier. The APD block encapsulates a driver amplifier, and a dual stage linearizer. The first stage of the linearizer, which comprises a T-network (C\textsubscript{3}, L\textsubscript{2} and C\textsubscript{4}), eliminates the low frequency components of the IMD\textsubscript{3} generated by the driver amplifier. These low frequency components are capable in generating low frequency nonlinear spurs through the coupling with the biasing circuit of the main amplifier under modulated transmission. This phenomenon is known as the bias modulation effect.\textsuperscript{13}

The generation of an opposite AM–AM response is accomplished once the second stage linearizer consists of C\textsubscript{5}, L\textsubscript{3} and C\textsubscript{6} is integrated. The low pass PI network will feed back the third–order component back to the output of the driver amplifier with an opposite phase response. This results a gain compression at location Y of Fig. 2. This technique is explained further with the aid of Fig. 3.

![Fig. 2. The schematic of the proposed PA with integrated dual stage linearizer network.](image-url)
Referring to the Smith plot in Fig. 3(a), points A and B denote the output impedance of the driver amplifier and input impedance of the main amplifier respectively as described in Fig. 2.

The component values of the dual stage linearizer is chosen to present an impedance $X$ at location $Y$ in order to generate an opposite AM–AM response respective to the main amplifier’s profile, thus cancelling out the IMD3 effect. This opposite AM–AM response can be viewed in Fig. 3(b). If the second stage linearizer is disabled, the impedance in location $Y$ is $B_{con}$ instead of $X$.

Fig. 3. (a) Various impedance points tapped at the output of the driver amplifier and location $Y$. (b) The AM–AM profile of the driver amplifier at location $Y$ as compared to the AM–AM profile of the main amplifier. The standalone main amplifier presents a gain expansion due to low biasing profile.

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4. Measurement Results

Figure 4 illustrates the micrograph of the 1 mm × 1 mm fabricated die with the bondwires intact. Evidently from Fig. 5, with the aid of the dual stage linearizer, the PA is able to meet −30 dBc ACLR specifications up to the output power of 30 dBm.

Fig. 4. Photomicrograph of the fabricated PA.

Fig. 5. Measured ACLR comparison between PA with and without dual stage linearizer at 1980 MHz. ACLR improves by 3 dB at low output power and more than 3 dB after surpassing 28 dBm.
in comparison to the operation of the PA if it is only biased at low quiescent current without any linearizer circuit intact. The dual stage linearizer also reduces the AM–AM effect in the design as well as improves the maximum output power, as illustrated in Fig. 6.

Fig. 6. Measured gain variation respective to the output power.

Fig. 7. Measured ACLR and PAE plot at 1.92 GHz and 1.98 GHz with the dual stage linearizer.
The fabricated PA is able to deliver 30 dBm of linear output power from the range of 1.92–1.98 GHz, complying the linear transmission requirement for LTE 20 MHz channel bandwidth, as illustrated in Fig. 7. Figure 8 illustrates the measured output spectra at an output power 30 dBm. With supply voltage headroom of 3.5 V and a quiescent current of 95 mA, the PAE of the PA is measured to be 38.29%.

Table 1 tabulates the measured performance summary of the microwave monolithic integrated circuit (MMIC), whereas Table 2 highlights the performance comparison of the proposed design.

Fig. 8. Measured output spectra at output power 30 dBm for 20 MHz channel bandwidth.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>1 mm × 1 mm</td>
</tr>
<tr>
<td>Process</td>
<td>InGaP/GaAs 2 μm HBT</td>
</tr>
<tr>
<td>Mode</td>
<td>LTE</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>1920–1980 MHz</td>
</tr>
<tr>
<td>Gain</td>
<td>31.3 dB</td>
</tr>
<tr>
<td>Linear output power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>PAE@30 dBm</td>
<td>38.29%</td>
</tr>
</tbody>
</table>
5. Summary

In this work, a highly linear PA which meets the specification for wideband LTE has been demonstrated. This PA is capable in delivering 30 dBm of linear output power for LTE with 20 MHz channel bandwidth. This is achieved with the aid of a novel dual-stage linearizer to cancel the IMD3 components generated by the PA. The improvement in maximum linear output power provides more headroom to compensate antenna path loss, which is significant in high frequency operation.

Acknowledgments

This research is supported by the eScienceFund 03-01-03-SF0783 from the Ministry of Science, Technology and Innovations.

References