FET Diode Linearizer Optimization for Amplifier Predistortion in Digital Radios

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***Abstract*—This letter presents the initial results in a study on a diode-based power amplifier (PA) linearization technique. The optimization of a diode's parameters to match a MESFET PA is discussed. The relevance of AM–AM and AM–PM curves to linearity requirements and modulation format is also discussed. As much as a 6.7-dB improvement in ACPR is made in the upper channel using a series diode linearizer.**

***Index Terms*—AM–AM, AM–PM, linearization, MESFET, nonlinear, power amplifier, predistortion.**

I. INTRODUCTION

THE HARDWARE linearity requirements of modern digital wireless communications systems have become very stringent due to the shrinking amount of available frequency spectrum, which results in the desire to use more complex modulation formats. Along with the need for highly linear hardware is the need for reduced power consumption and component size for portability. Linear amplifiers are known to be very inefficient. This results in the need for the development of highly linear yet efficient amplifiers. One of the largest current sinks in a radio is the transmit power amplifier (PA); thus, this is an obvious target for improvement. The basic idea is to take an already efficient PA, which is inherently nonlinear, and introduce additional circuitry to make it more linear. AM–AM and AM–PM curves are useful in characterizing an amplifier's linearity [1]–[3]. In addition, the flattening of these curves may lead to a reduction in adjacent channel power ratio (ACPR), also known as spectral regrowth. ACPR is becoming the standard for linearity characterization in modern wireless communications. This is partly since the amplitude statistics of a two-tone signal used for IMD analysis are much different than those of digitally modulated signals [3].

II. LINEARIZER CIRCUIT

A possible linearizer circuit was proposed in [4] to provide AM–AM and AM–PM compensation with minimal circuitry resulting in modest ACPR improvements. A schematic of this linearizer is shown in Fig. 1.

A similar circuit is proposed in [5], which consists of a shunt diode across the base-emitter junction of an HBT PA. Other diode predistortion linearizers have been proposed in [6] and [7], which work through harmonic distortion generation opposite in phase to the distortion created by the PA, however this requires accurate phase control and additional bulky circuitry, which is not conducive to MMIC integration, compared to that proposed in [4]. For the circuit in Fig. 1, the diode functions as a nonlinear resistor (R_D) with a parasitic capacitance (C_P) in parallel. Since the diode is operated under a forward bias, the nonlinear C/V is neglected. This resistance and capacitance is used to form a nonlinear RC phase shift network. Additional R and C may be added externally if needed, but in this work the diode size is optimized to obtain the required R and C. The diode is biased to set R_D and C_P at an initial small signal operating point. An input power sweep on a vector network analyzer (VNA) shows that as the diode is driven past small signal with radio frequency (RF) power, the diode rectifies the RF power and the operating point changes with increasing input power. Effectively, R_D decreases with increasing input power since its operating point is moved up the I/V curve. R_D changes nonlinearly due to the diode's I/V characteristic, resulting in a nonlinear phase shift with increasing input power. The following equation gives S_{21} for the RC network:

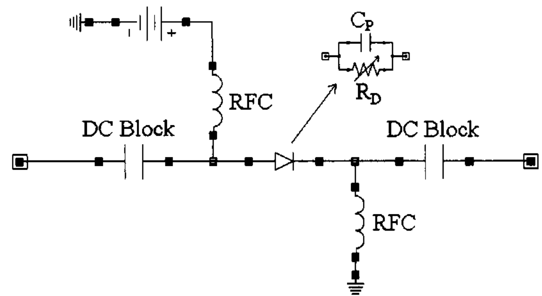

Fig. 1. Diode linearizer schematic.

$$S_{21} = \frac{2Z_0Y}{1+2Z_0Y}, \quad Y = j\omega C_P + \frac{1}{R_D}. \tag{1}$$

Inspection of (1) shows a resulting gain expansion and decrease in phase shift for a decreasing R_D. Typically, amplifiers driven into their nonlinear regions exhibit gain compression and phase advance. This is opposite to that of the diode linearizer circuit, thus this circuit should be able to compensate for these nonlinear amplifier characteristics. A more detailed treatment on this subject may be found in [4].

III. DIODE OPTIMIZATION

A nonlinear MESFET PA is the focus of this study, thus a drain–source connected MESFET is used for our diode. To optimize the diode for this application, a study of S-parameters

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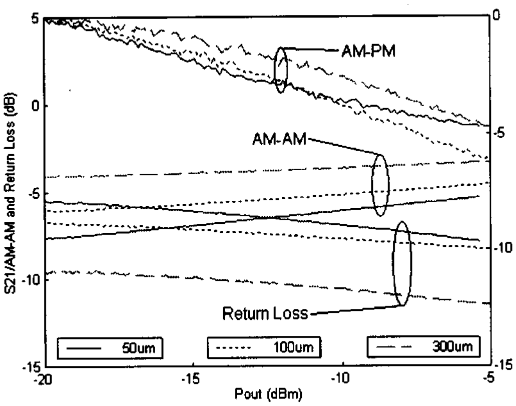

Fig. 2. 50-, 100-, and 300-μm diode parameters.

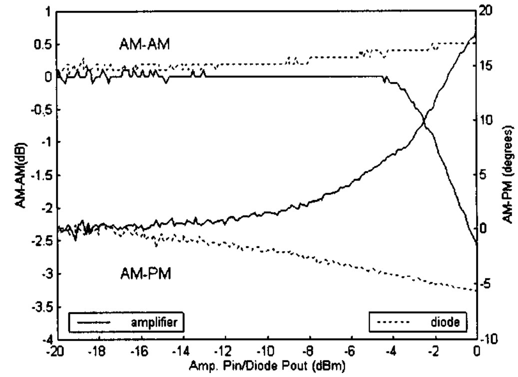

Fig. 3. PA and diode AM–AM and AM–PM normalized to the small-signal gain/loss and phase.

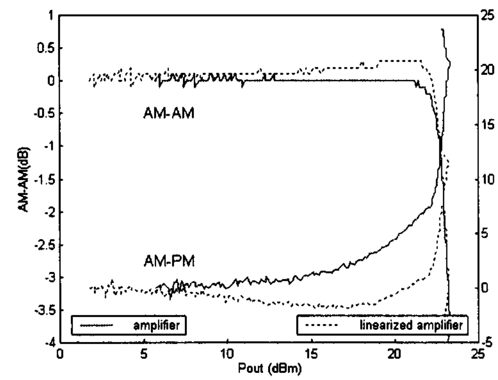

Fig. 4. PA AM–AM and AM–PM before and after linearizer normalized to the small-signal gain/loss and phase.

versus bias, size, and input power was performed. 50–2400-μm gate periphery diodes were studied at 1.9 GHz. It was found that the larger diodes require much more drive level to get a change in operating point due to RF rectification. Thus, a PA requiring higher input drive level before going nonlinear will require a larger diode. In addition, at ~0.6 V forward bias, a medium sized diode (~500 μm) exhibits the smallest insertion loss (IL) as well as the best return loss (RL) at small signal for this process, obviating the need for external matching. In addition, this optimization of RL removes the need for isolators as used in [4]. This improves the ability to easily integrate this linearizer as part of an RFIC or MMIC. An inspection of the circuit's AM–AM curve shows a decrease in IL with increasing input power, or "gain expansion." This circuit must be driven harder to overcome the IL. This represents a drawback of this linearization scheme. In addition to the above considerations, the required AM–AM and AM–PM compensation for the PA to be linearized must be considered.

Fig. 2 shows a plot of the AM–AM, AM–PM, and RL for a 50-, 100-, and 300-μm diode. The bias for each diode was adjusted to get about 5° of AM–PM. Adjustment of this bias provides an extra degree of freedom in adjusting the diode AM–AM, AM–PM, RL, and IL once the diode size has been chosen. The diode plots are made versus output power since this will be the power arriving at the PA input. This way the diode IL may be neglected for the time being. It can be seen that for about the same AM–PM, the larger diode has less IL, higher RL, and less AM–AM. The larger diode is approaching 50 Ω, which means that this diode will have minimal impact on the input match of the PA. In addition, for a lower IL, less extra input drive is needed to properly drive the PA. This is important since if an ACPR improvement is made, but the new circuit requires much more drive than the stand alone PA, then the nonlinearities of the driver stage may come into play. A small amount of AM–AM correction (a few tenths of a decibel) is possible, but it is very hard to keep the diode AM–AM flat and then correct for the severe AM–AM of the PA as it goes into saturation. Since it is easier to correct the AM–PM, this is the focus of these initial studies.

The target amplifier was a MESFET PA tuned to operate at 2.68 GHz. The diode size and bias is optimized to compensate the AM–AM and AM–PM of this PA. An inspection of the diode parameters as previously discussed, but at 2.68 GHz, along with the PA characteristics shows that a 500-μm diode biased at 0.57 V will provide the necessary compensation with an input small signal RL of ~15 dB and IL of ~2.2 dB. The effect of going to a higher frequency is reduced parasitic capacitive impedance. Fig. 3 shows the diode and PA AM–AM and AM–PM curves. Fig. 4 shows the results of this diode and PA together to form a linearized PA. The test setup consisted of a PCB designed for biasing and testing a series diode, which was connected in front of the PA PCB with SMA connectors. Note that a linear phase shift of S21 on the test boards is not a problem, it is the nonlinear phase shift that is being corrected. From these plots, a reduction of the PA's AM–PM may be seen along with a small reduction in the AM–AM just before the 1-dB compression point. In [1], the importance of AM–PM reduction is stressed, thus this design was optimized for maximum AM–PM compensation.

IV. A CONSIDERATION OF MODULATION

The type of modulation used in a radio system puts different demands on the linearity requirements of the system. Some form of QPSK modulation is becoming popular which has a nonconstant envelope that exhibits a peak envelope power (PEP), higher than the signal's average power. If a modulated signal drives an amplifier at an average power level, an average operating point on the amplifier's AM–AM and AM–PM curves may be established. The signal PEP causes deviations from this operating point, driving an amplifier further into compression when a peak in the envelope arises. Thus, for increasing PEP a nonlinear amplitude and phase distortion occurs on the signal [8]. This shows the importance of AM–AM and AM–PM curves in characterizing nonlinearities for modulated signals. Different forms of modulation exhibit different peak-to-average-ratios (PTAR, i.e., PEP relative to average power), thus some are more susceptible to nonlinearities. In addition, the choice of baseband filtering will have an effect on the PTAR, thus impacting the linearity requirements. For these reasons, the amplifier designer can no longer merely use a CW compression point when designing for a digital radio system and choosing a back-off point to meet linearity requirements. They must now consider the PTAR of the signal along with the amplifier compression point. To remain relatively linear, the amplifier must now be backed-off to keep the PEP below the compression point. A more in depth treatment of this may be found in [8]. It is important to note that this treatment on nonlinearity deals with operation in an amplifier's strongly nonlinear region, where efficiency is typically highest, but in the weakly nonlinear region AM–AM and AM–PM curves lose their usefulness.

V. ACPR Results

For the linearized PA previously discussed, a set of ACPR measurements was performed and summarized in Table I. ACPR was measured for some common types of complex digital modulation with different PTAR for an average output power of +15 dBm. In the linearized PA case, the input power is increased to overcome the linearizer IL. ΔUACPR/ΔLACPR is the upper/lower channel ACPR *improvement* due to the linearizer. The baseband filtering used is the IS95 specified filter for a CDMA mobile station. ACPR was measured in a 30-kHz channel 1.25 MHz away from f_c for a 1.25-MHz chip rate. This shows that the linearizer helps most for signals with a lower PTAR. A high PTAR pushes the signal much further into the compression region, having a much more detrimental effect due to the nonlinearity. This shows that flattening AM–PM results in an improved ACPR. For higher output power where the PA is operating further into compression, there is less or no envelope correction from the linearizer, thus there will be less or no improvement in ACPR as power increases. At small signal or high back-off, the only effect of the linearizer is to introduce IL, thus there will be no improvement in ACPR at high back-off conditions. This means that the linearizer works best at points of slight back-off from compression. The discrepancy between upper and lower ΔACPR is currently under investigation. In [8], the asymmetry due to AM–PM is discussed in the context that different device mechanisms create AM–AM and AM–PM. The phase difference between the mechanisms causing AM–AM and AM–PM may be introducing the asymmetry problem. The fact that AM–PM IMD products may constructively or destructively add with the AM–AM IMD products due to this phase difference may account for the asymmetry. Further investigation is necessary to explore reduction or elimination of the asymmetry.

TABLE I
LINEARIZED PA ACPR IMPROVEMENT VERSUS PTAR AT AN AVERAGE OUTPUT POWER OF +15 dBm

Modulation	PTAR (dB)	ΔUACPR (dB)	ΔLACPR (dB)
QPSK	6.84	5.8	2.2
OQPSK	5.49	6.7	1.7
Pi/4 DQPSK	6.14	5.7	1.6
16 QAM	9.37	4.9	1.8
256 QAM	11.05	4.9	2.1

VI. Conclusions

A 2.68-GHz MESFET amplifier has been linearized with a series diode AM–AM and AM–PM compensation using minimal circuitry. The improvement in ACPR has been measured for modulation with different PTAR. OQPSK had the smallest PTAR with a 6.7-dB improvement in one sideband, while 256 QAM had the highest PTAR with a 4.9-dB improvement in one sideband. We have shown that a reduction in AM–PM using the optimized series diode linearizer presented here does lead to an improvement in ACPR; however, the linearizer may be optimized for either AM–AM or AM–PM, or both. An overview of how to optimize the diode size for minimum IL and maximum RL has been discussed. With this improvement, the linearized PA may exhibit an improved ACPR over the stand alone PA with the same output power. However, the requirement of more drive level to overcome the 2.2-dB small-signal IL of this linearizer circuit must be weighed carefully with efficiency requirements.

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