Software-Based Adaptive Protection Control against Load Mismatch for a Mobile Power Amplifier Module

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Abstract: A closed-loop protection method for a radio frequency (RF) power amplifier (PA) module applicable to mobile handsets has been introduced. The load impedance of the PA was adaptively sensed by an embedded impedance detector which was digitally controlled and the system adjusted PA power using a feedback circuit to keep the PA safe based on a load mismatch detection. For verification, a two-stage hetero junction bipolar transistor (HBT) PA module for handsets was fabricated and tested against load mismatch. Measurement results showed that the technique could help PA survive at a 0.5V larger collector bias voltage condition than when the technique was not applied for the same mismatch condition with an acceptable RF performance degradation at nominal condition.

Keywords: RF power amplifier; protection circuit; load mismatch; impedance detection; closed loop feedback; HBT; mobile industry processor interface (MIPI); software; module

1. Introduction

One of the basic requirements for radio frequency (RF) power amplifiers (PAs) in mobile devices is a sufficient ruggedness which means an ability to survive under a severe antenna mismatch condition. Several approaches have been developed to prevent solid state PAs from being damaged against load mismatch. In previous generations of handsets, it was general to implement an isolator between the PA module and the handset antenna in order to isolate the amplifier from changes in impedance at the antenna port, which is incompatible with modern handsets due to the size and cost limits [1]. Other solutions including improved process [2,3], resistive emitter ballasting [4], and various open-loop/closed-loop techniques [5–12] have been proposed. Among these solutions, the closed-loop techniques have been developed in various configurations according to the sensing object and the feedback form. For example, they can detect the voltage or current of the final stage of PA and use a feedback circuit to clamp the input/output voltage or to control the bias circuit to reduce the driving power level. However, since the target to be detected depends on the cause of a PA failure, appropriate system configuration is necessary according to the situation. In particular, PAs operating under various conditions such as multi-mode multi-band (MMMB) PA should be able to cope with various failure causes because the failure mechanism varies according to the conditions such as operation mode or frequency band. Existing approaches have to be equipped with each solution at the same time in order to cope with various causes, which makes the system much more complicated. To overcome this issue, a protection system needs to recognize the risk regardless of the type of failure. Then, by recognizing dangerous situations and operating a feedback circuit adaptively as stated above, the PA can be protected from damages.
In this paper, an adaptive protection method for PAs using a software-controlled dynamic mismatch detection and bias control technique is proposed. This method was developed based on the idea that the PA failure situation can be predicted regardless of its mechanism by recognizing the location of the load impedance. To demonstrate the feasibility of the proposed method, a RF PA module for mobile communication system was fabricated and tested employing a control logic.

2. Closed-Loop Protection Circuit

In a previous study [13], two categories of breakdown and thermal runaway were found to determine the ruggedness of a hetero junction bipolar transistor (HBT) PA which is mainly used in recent handsets. Severe mismatch conditions at the antenna terminal result in very large voltage peaks or current peaks at the collector of the PA’s final stage, in turn, the voltage peaks can lead to breakdown and current peaks can lead to thermal runaway, resulting in a permanent damage to the PA. Figure 1 shows the impedance mismatches that cause these two types of failures. Figure 1a and 1b describe the mismatched impedance at antenna terminal ($\Gamma_0$) and at the PA collector ($\Gamma_1$), respectively and Figure 1c shows the reference planes of these impedances. $\Gamma_1$ is the impedance which is transformed from $\Gamma_0$ by the output matching network.

![Figure 1](image_url)

Figure 1. Two impedance mismatch cases that can cause power amplifier (PA) failures: (a) mismatched impedance at antenna terminal ($\Gamma_0$); (b) mismatched impedance at PA's final stage ($\Gamma_1$); (c) reference planes of (a) and (b).

The mismatch that forms the high impedance at the PA collector (B in Figure 1a, B' in Figure 1b) generates the voltage peak, and the mismatch that forms the low impedance (A in Figure 1a, A' in
Figure 1b) generates the current peak. Figure 2 depicts a typical closed-loop protection circuit, which usually consists of a sensing circuit and a control circuit. The type of the sensing circuit should be determined according to whether it senses voltage or current, which depends on the failure mechanism such as breakdown or thermal runaway. Since PAs are vulnerable to breakdown and thermal runaway depending on conditions, MMMB PAs operating under various conditions will have different targets to detect with the operating condition. In this case, the conventional protection circuit must be able to detect both voltage and current respectively depending on situations to cope with various failure causes. However, this feature may increase the complexity of protection circuits. Moreover, if the PA fails due to a failure factor other than current/voltage, the current and/or voltage measurement methods cannot protect the PA. For example, a thermal issue due to large dissipated power \( (P_{\text{diss}}) \) can cause the PA to fail and it is known that \( P_{\text{diss}} = P_{\text{dc}} - P_{\text{RF}} \). Using the detected voltage/current, \( P_{\text{dc}} \) can be estimated but \( P_{\text{RF}} \) is hard to estimate. Therefore, this kind of method is not able to protect the PA in some cases. On the other hand, the impedance detection method can clearly determine whether or not the situation will cause PA failure regardless of the cause of the failure.

![Typical closed-loop protection scheme.](image.png)

**Figure 2.** Typical closed-loop protection scheme.

In this paper, a closed-loop protection circuit with an advanced sensing scheme is proposed; the sensing circuit senses impedance rather than voltage or current. Since PA failure is directly related to load impedance, PAs can be more reliably protected by detecting a predetermined failure impedance area, regardless of the failure mechanism. Hence, a closed-loop protection circuit which adaptively senses impedance and adjusts the input power of the final stage is presented in following sections.

### 3. Operating Principle of Proposed Protection Method

As shown in Figure 2, the typical closed-loop protection circuit detects whether a voltage or a current exceeds a specified level and controls the gain (or power) of the PA for protection. This method can generally only detect voltage or current. Thus, there is a problem in that each solution must be combined to detect both, which increases the system complexity.

In author’s previous work [14,15], a dynamic mismatch impedance detector and corrector were proposed to recover RF PA’s performances such as adjacent channel leakage ratio (ACLR) and power added efficiency (PAE) which degrade under mismatch condition. Unlike in the previous work, this work used a similar impedance mismatch detector to improve ruggedness, not ACLR or PAE. Figure 3 shows the block diagram of the proposed protection scheme.

#### 3.1. Mismatch Impedance Detector

The load impedance region where PA failure occurs can be identified in advance through load-pull characterization. Thus, when the load impedance happens to be in this “failure impedance zone”,...
the PA can be protected by recognizing the load impedance and adjusting the PA state. This dangerous impedance region is located in a specific load phase (\(\angle \Gamma_L\)) section where a voltage standing wave ratio (VSWR, \(|\Gamma_L|\)) is large. However, the \(|\Gamma_L|\) area larger than 0.7 needs not be considered because it is an impractical region when considering the post-PA loss which is generally larger than 1.5 dB.

The mismatch impedance detector sensed the \(|\Gamma_L|\) and \(\angle \Gamma_L\), respectively, and used a combination of the two results to determine if the load impedance was in the failure area. The proposed mismatch impedance detector was composed of a \(|\Gamma_L|\) detector, a \(\angle \Gamma_L\) detector including a phase shifter, and a control logic circuit that controlled the phase shifter to define various impedance sections to detect as shown in Figure 4a.

The \(|\Gamma_L|\) detector in Figure 4a was implemented as a simple voltage detector and used \(V_{coup}\) (coupling port voltage) and \(V_{iso}\) (isolation port voltage) to create a \(V_M\) (magnitude detector output voltage) with a “high” value when \(|\Gamma_L|\) was above a specified \(|\Gamma_L|\) value. Basically, \(|\Gamma_L|\) detection could be done with \(V_{iso}\) alone, but \(V_{coup}\) was also needed to compensate for changes such as process, voltage and temperature.

Figure 4b shows the block diagram of the \(\angle \Gamma_L\) detector and it extracts \(\angle \Gamma_L\) position using the fact that the difference between \(V_{coup}\) and \(V_{iso}\) is a function of the load phase. As shown in Figure 4c, \(V_{ph}\) (phase detector output voltage) with high value in a specific \(\angle \Gamma_L\) section was generated by comparing \(V_{diff}\), which is the difference between \(V_{coup}\) and \(V_{iso}\), and \(V_{ref}\), which is a reference. Therefore, if \(V_{ph}\) has a “high” value, it means that the current load phase belongs to the specific phase section, and if it has a “low” value, it means that it is outside the section. In addition, by using a phase shifter at the input of the \(\angle \Gamma_L\) detector as shown Figure 4a, it was possible to adjust the detection target phase section. The detailed configuration of the reconfigurable phase shifter is shown in Figure 4d, which was adaptively controlled by the control circuit to define various load phase sections. Two \(V_{ph}\) detections by changing the phase of the phase detector allowed the combination of the results to determine where the current \(\angle \Gamma_L\) belonged to among the four preset phase section regions. Figure 5 illustrates the process of determining which region the current \(\angle \Gamma_L\) belonged to, assuming that the \(|\Gamma_L|\) was determined by the \(|\Gamma_L|\) detector. Table 1 shows an example of detecting load impedance section from the \(V_{ph}\) value set obtained from a procedure shown in Figure 5a. The designation of the impedance area to be detected could be easily set in any area through the design of the \(|\Gamma_L|\) detector and the \(\angle \Gamma_L\) detector, and the size of the detection area could be adjusted according to the situation by using a reconfigurable phase shifter which was controlled through the mobile industry processor interface (MIPI). The more detailed operating principles of this technique have been previously provided [14,15].
If this detection described above confirmed that the current load impedance was in the failure impedance zone, the algorithm allowed the “Decision and control circuit” to reduce the power of the PA.

Figure 4. (a) Proposed mismatch impedance detector; (b) block diagram of phase detector; (c) simulated $V_{\text{diff}}$, $V_{\text{ref}}$ and $V_{\text{ph}}$; (d) reconfigurable phase shifter configuration; (e) simulated $V_{\text{diff}}$, $V_{\text{ref}}$ and $V_{\text{ph}}$ for two phase values of phase shifter.
is constructed. Bias and therefore had little impact on PA performance. Figure 6 depicts a block diagram of how this is detected.

Figure 6. Block diagram of proposed closed-loop protection circuit.

Table 1. Example of detecting section from $V_{ph}$ value set. (Figure 5a).

| Index | $V_{ph}$ (1st) | $V_{ph}$ (2nd) | Detected Section $^1$ |
|-------|---------------|---------------|-----------------------|
| 1     | L             | H             | #1                    |
| 2     | L             | L             | #2                    |
| 3     | H             | L             | #3                    |
| 4     | H             | H             | #4                    |

$^1$ Assuming that $|\Gamma_L|$ is determined by VSWR ($|\Gamma_L|$) detector.

3.2. Adaptive Power Control for Protection

Most closed-loop protection schemes protect the PA through gain control, which is the same as adjusting the output power since the input power is usually fixed to one value during the ruggedness test. Previous methods control output power by intentionally mismatching the input matching network of PA, adjusting the drive stage bias, or adjusting the final stage bias when a dangerous situation is detected.

In this work, when the load impedance of the PA fell into a failure impedance zone, the base bias voltage of the drive stage was sufficiently lowered to reduce the output power of the drive stage and consequently to reduce the power of the final stage for PA protection. This only adjusted the PA bias and therefore had little impact on PA performance. Figure 6 depicts a block diagram of how this is constructed.
Figure 7a shows the simulation result of the drive stage power ($P_{drv}$) according to the change of the drive base bias voltage ($V_{reg, drv}$). Since $P_{drv}$ was the input power of the final stage, decreasing it also reduced the output power ($P_{out}$) of the final stage. From the simulation result in Figure 7b, it was confirmed that PA used in this paper should have reduced $V_{reg, drv}$ from the usual 2.8 V to 1.2 V or less to reduce the power by at least 2 dB, thereby protecting a PA from the damage. In order to confirm that the feedback circuit operated at high speed, the time constant of each circuit was estimated by simulation. The results are as follows.

![Simulation result of (a) drive stage power over the drive base bias voltage ($V_{reg, drv}$); (b) final stage power over $V_{reg, drv}$](image)

Figure 7. Simulation result of: (a) drive stage power over the drive base bias voltage ($V_{reg, drv}$); (b) final stage power over $V_{reg, drv}$.

- Time constant of detection circuit <0.3 µs
- PA bias switch time (time between MIPI write changing PA bias and settled PA gain) <2 µs
- It confirmed that the circuit’s operating speed was much smaller than a typical thermal time constant.

4. Fabrication and Measurement

For the verification of the proposed adaptive protection method, a RF PA module was fabricated by applying the technique. The PA monolithic microwave integrated circuit (MMIC) was designed as a two-stage amplifier and was fabricated using a 2-µm InGaP/GaAs HBT process. The emitter areas of the first and final stage were 500 and 3600 µm$^2$, respectively. The mismatch impedance detector and the band-selection switch was fabricated using a 0.18 µm silicon on insulator (SOI) complementary metal oxide semiconductor (CMOS) process. The controller circuit was also fabricated using 0.25 µm Si CMOS process. All of these integrated circuits (ICs) were implemented into a single module on an FR4 substrate as shown in Figure 8a. The off-chip directional coupler (CP0402AE) was also mounted in the module. Figure 8b shows the enlarged photograph of the core area in the module with names of each component.

To confirm that the ruggedness of PA was improved, measured output power was compared with and without the protection technique using the measurement setup where all instruments were controlled by a dedicated program shown in Figure 9. The measurements were performed at mismatched condition using a 5 MHz 1 RB long-term evolution (LTE) signal of 10 dBm over collector voltage (Vcc) at 2017.5 MHz (Band 34). When the closed-loop protection technique was deactivated, the PA module was damaged over a certain $\Delta L_{L}$ range ($30^\circ < \Delta L_{L} < 90^\circ$) with $|\Gamma_{L}| > 0.6$. After confirming the location of the failure zone, the mismatch impedance detector was set to identify whether $\Gamma_{L}$ was in this area or not through MIPI. Since the detector’s output could be unstable when the load impedance was at the boundaries of the predetermined impedance sections, the detector was designed to have hysteresis characteristics to avoid this situation. As a result, the module activating the protection
technique survived at higher Vcc condition than when the technique was deactivated. Figure 10 shows the measured output power comparison between activating and deactivating the proposed technique at $|\Gamma_L|$ of 0.7 under Vcc of 5.5 V. When protection was not applied, the PA was damaged in the failure impedance zone and did not provide normal power. However, when protection was applied, the PA output power was sufficiently backed off and a PA failure did not occur. From the comparison, it was confirmed that the proposed technique improved the ruggedness of the PA.

![Photograph of assembled module](image1)

(a)  

(b)  

**Figure 8.** Photograph of: (a) assembled module; (b) enlarged core area with names of each component.

![Block diagram of test setup](image2)

(a)  

![Photograph of measurement setup](image3)

(b)  

**Figure 9.** Measurement setup for ruggedness test. (a) Block diagram of test setup; (b) photograph of the measurement setup.
The measured ruggedness over Vcc ($|\Gamma_L| = 0.7$) are shown in Table 2 where the module with protection technique showed better ruggedness in terms of Vcc by 0.5 V than that without the protection technique. Since this technique only changed the PA bias under mismatch conditions, there was no performance difference between activating and deactivating the proposed technique. However, the loss caused by the addition of the directional coupler caused PAE degradation, but this was acceptable. (PAE degradation less than 1% for envelope tracking (ET) operation mode.) The disadvantages in terms of power consumption and size from the added circuits should be improved in the future.

| Frequency (MHz) | Supply Voltage (V) | Deactivating Protection | Activating Protection |
|-----------------|--------------------|-------------------------|-----------------------|
| 2017.5          | 4.5                | Passed                  | Passed                |
| 2017.5          | 5.0                | Passed                  | Passed                |
| 2017.5          | 5.5                | Failed                  | Passed                |
| 2017.5          | 6                  | -                       | Failed                |

5. Conclusions

An adaptive protection circuit for mobile power amplifiers has been proposed based on a dynamic impedance detection which is digitally controlled through a MIPI interface. This approach protects the PA by reducing the power of the PA by using a feedback circuit based on the mismatch impedance sensing result provided by the impedance detector when the PA load impedance approaches a failure load impedance zone. Since this method senses impedance rather than voltage or current, protection is possible regardless of the PA failure mechanism. A RF PA module for mobile handsets with the technique was designed and fabricated to demonstrate the effectiveness of the approach. When the ruggedness test was performed at Band 34, it was confirmed that the PA survived at about a 0.5 V larger Vcc condition than when this technique was not applied with an acceptable ET PAE degradation less than 1%. The results achieved confirm that the proposed protection circuit can improve the ruggedness of PA effectively.

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