

NOTE: The theory in this application note is still applicable, but some of the products referenced may be discontinued.

# Quiescent Current Thermal Tracking Circuit in the RF Integrated Circuit Family

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## INTRODUCTION

During a power amplifier design phase, an important item for a designer to consider is the management of performance over temperature. One of the main parameters that affects performance is the quiescent current. The challenge for a designer is to maintain constant quiescent current over a large temperature range. The problem becomes more challenging in a multistage IC (integrated circuit). To overcome this difficulty, Freescale has embedded a quiescent current thermal tracking circuit in its recently introduced family of RF power integrated circuits.

This application note reviews the tracking circuit implemented in the RF power integrated circuit family, its static characterization and its impact on linearity.

This information is applicable to the MW4IC2020, MW4IC2230, MWIC930, MW4IC915, MHVIC2115 and MHVIC915 products.

First is a review of the LDMOS thermal behavior, then an analysis of the thermal tracking circuit and its functioning. A discussion of how it reacts to different bias sources follows, and the capability of the user to disable it. The next part discusses the characterization results of the thermal tracking under DC conditions. Finally, the characterization under RF conditions is presented.

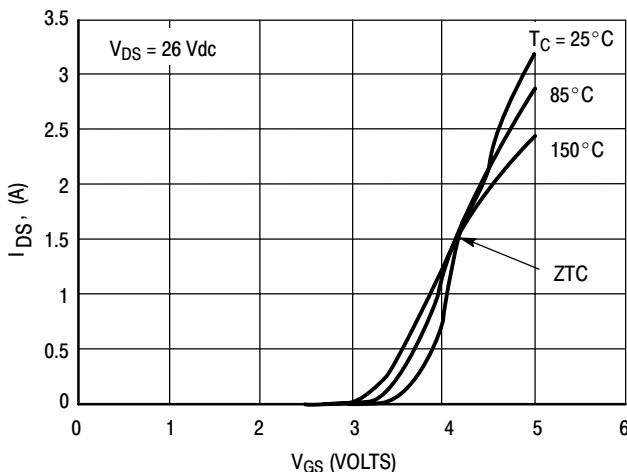


Figure 1.  $I_{DS}$  versus  $V_{GS}$  and Case Temperature

## LDMOS THERMAL BEHAVIOR

Figure 1 presents the quiescent current thermal behavior of a 30 Watt LDMOS device.

The drain-source current is strongly impacted by temperature. In Class AB and for a given  $V_{GS}$ , the  $I_{DQ}$  rises with temperature. Consequently, the shapes of the AM/AM response as well as linearity are affected by temperature.

Figure 2 presents the third order IMD for a 2-tone CW excitation for two different quiescent currents. As expected, the  $I_{DQ}$  variation has a strong effect on the third order IMD behavior.

## CIRCUIT IMPLEMENTATION

The thermal tracking device is a very small integrated LDMOS FET transistor that is located next to the active LDMOS die area on the die. There are several such thermal tracking FETs in an LDMOS IC.

A thermal tracking transistor has its gate and drain connected together, and its source is connected to ground (see Figure 3).

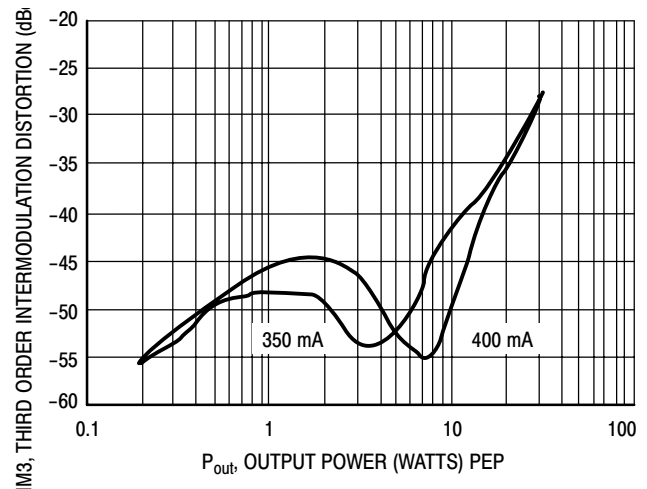
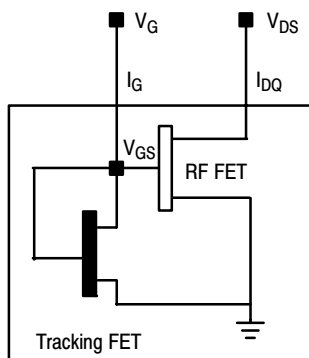
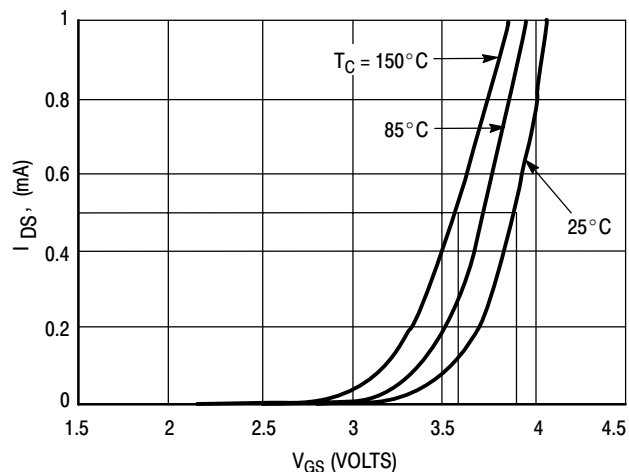


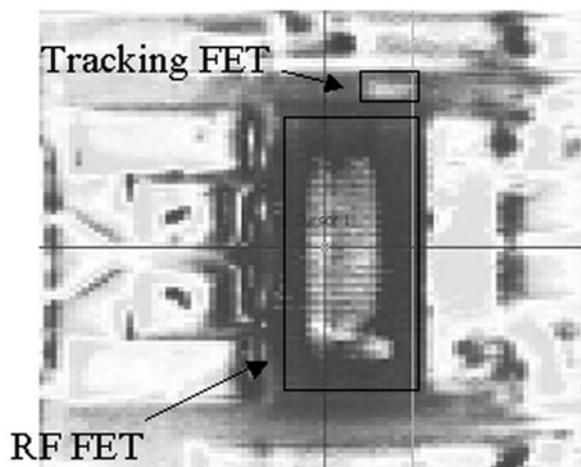
Figure 2. Third Order Intermodulation Distortion versus Quiescent Current, Single Stage



**Figure 3. Thermal Tracking Schematic**



**Figure 4. Thermal Tracking FET, DC Characteristic**



**Figure 5. Infrared Picture**

When a constant current source is applied to  $V_G$ , the thermal tracking FET draws a constant current  $I_G$ ; when the temperature varies, the voltage  $V_{GS}$  varies to maintain the constant current  $I_G$ .

As a consequence, the LDMOS power FET sees a varying gate voltage,  $V_{GS}$  (from 3.6 to 3.8 Volts as shown in Figure 4) that also maintains its  $I_{DQ}$  constant with temperature. The tracking FET acts as a mirror of the RF FET. Consequently, the thermal tracking is independent of the quiescent current and the temperature.

When a constant voltage source  $V_G$  is applied, the voltage is set on the thermal tracking transistor, and its current varies with a change in temperature. Therefore, the thermal tracking is disabled.

Note that the ratio  $I_{DQ}/I_G$  is set by design; it reflects the size of the two transistors: RF FET gate periphery and tracking FET gate periphery.

The RF FET is biased at  $V_{DS} = 26$  to 28 Volts while the tracking FET is biased around  $V_{DS} = 3$  to 4 Volts, depending on the quiescent current needed. Although the two FETs are

biased in different conditions, the  $I_{DS}$  versus  $V_{GS}$  curves behave almost identically over temperature under nominal conditions of operation. In other words, the thermal coefficient remains constant for  $V_{DS} = 3.5$  to 4 Volts and 26 to 28 Volts and for a given  $I_{DQ}$ .

During operation, the RF FET is biased at 26 Volts and in Class AB while the tracking FET is biased at  $V_{DS} = 3$  to 4 Volts. Therefore, the power dissipation is significantly different; consequently, the two die are not at the same temperature (see Figure 5).

Under DC conditions, the temperature difference can be significant. RF FET is at a higher temperature than its associated thermal tracking FET, and the ratio  $I_{DQ}/I_G$  is higher than the theory.

## CIRCUIT CHARACTERIZATION

As described earlier, a current source is needed to power on the thermal tracking. There are several ways to supply a constant current source.

The simplest way to realize a current source is to implement a resistor  $R_G$  in series in the gate bias circuit. The quiescent current is measured and adjusted by varying  $V_G$  (see Figure 6). Depending on the IC and desired  $I_{DQ}$ , the gate draws a current up to 5 mA.

For a better understanding of the thermal tracking constant current behavior, the following example is presented. This example uses a 2-stage 900 MHz IC (the MHVIC915) that is characterized over temperature for two different values of  $R_{GATE}$ . ( $R_{GATE} = 4.51 \text{ k}\Omega$  and  $R_{GATE} = 1 \text{ k}\Omega$ )

Tables 1 and 2 show the different DC voltage and DC current readings versus temperature for the second stage in this IC.

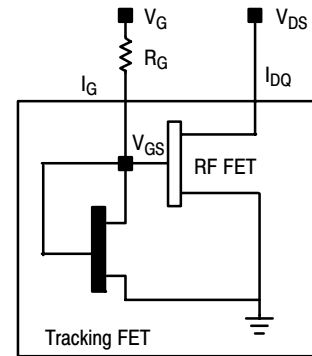
In this example, over a 100 degree range, the gate current varies about 5% with a 4.5 k $\Omega$  resistor and about 21% with a 1 k $\Omega$  resistor. This variation induces a variation of 8% on the  $I_{DQ}$  of the power stage in the first case and 25% in the second case.

**Table 1.  $I_{DQ}/I_G$  versus Temperature ( $R_G = 4.51 \text{ k}\Omega$ )**

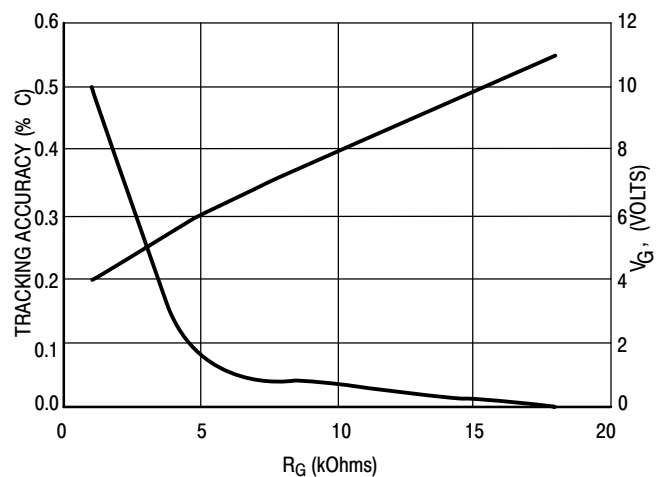
| Temp | $V_G$ (V) | $V_{GS2}$ (V) | $I_{G2}$ (mA) | $I_{DQ2}$ (mA) | $R_G$ (k $\Omega$ ) |
|------|-----------|---------------|---------------|----------------|---------------------|
| 100  | 8.55      | 3.75          | 1.023         | 266            | 4.51                |
| 90   | 8.55      | 3.77          | 1.018         | 264            | 4.51                |
| 80   | 8.55      | 3.79          | 1.013         | 262            | 4.51                |
| 70   | 8.55      | 3.81          | 1.008         | 260            | 4.51                |
| 60   | 8.55      | 3.83          | 1.003         | 258            | 4.51                |
| 50   | 8.55      | 3.85          | 0.998         | 256            | 4.51                |
| 40   | 8.55      | 3.87          | 0.993         | 254            | 4.51                |
| 30   | 8.55      | 3.89          | 0.988         | 252            | 4.51                |
| 20   | 8.55      | 3.91          | 0.983         | 250            | 4.51                |
| 10   | 8.55      | 3.93          | 0.978         | 248            | 4.51                |
| 0    | 8.55      | 3.95          | 0.974         | 246            | 4.51                |
| -10  | 8.55      | 3.97          | 0.966         | 243            | 4.51                |
| -20  | 8.55      | 3.99          | 0.962         | 241            | 4.51                |
| -30  | 8.55      | 4.01          | 0.958         | 240            | 4.51                |
| -40  | 8.55      | 4.03          | 0.953         | 238            | 4.51                |

**Table 2.  $I_{DQ}/I_G$  versus Temperature ( $R_G = 988 \text{ Ohm}$ )**

| Temp | $V_G$ (V) | $V_{GS2}$ (V) | $I_{G2}$ (mA) | $I_{DQ2}$ (mA) | $R_G$ (Ohm) |
|------|-----------|---------------|---------------|----------------|-------------|
| 100  | 4.89      | 3.65          | 1.168         | 294            | 988         |
| 90   | 4.89      | 3.68          | 1.147         | 289            | 988         |
| 80   | 4.89      | 3.71          | 1.126         | 283            | 988         |
| 70   | 4.89      | 3.74          | 1.105         | 278            | 988         |
| 60   | 4.89      | 3.77          | 1.084         | 272            | 988         |
| 50   | 4.89      | 3.8           | 1.063         | 267            | 988         |
| 40   | 4.89      | 3.83          | 1.042         | 261            | 988         |
| 30   | 4.89      | 3.86          | 1.021         | 256            | 988         |
| 20   | 4.89      | 3.89          | 1             | 250            | 988         |
| 10   | 4.89      | 3.92          | 0.967         | 242            | 988         |
| 0    | 4.89      | 3.95          | 0.95          | 235            | 988         |
| -10  | 4.89      | 3.97          | 0.93          | 233            | 988         |
| -20  | 4.89      | 3.99          | 0.912         | 228            | 988         |
| -30  | 4.89      | 4.01          | 0.894         | 224            | 988         |
| -40  | 4.89      | 4.01          | 0.874         | 217            | 988         |



**Figure 6. Thermal Tracking Schematic with its Bias Circuit**



**Figure 7. Tracking Accuracy and  $V_G$  versus  $R_G$**

The explanation for 5% variation instead of 21% is quite simple. Consider that, due to an external phenomenon (increasing temperature for instance), the  $I_G$  current increases. As  $V_G$  is fixed by the supply, the drop through the  $R_{GATE}$  resistor also increases. This, in turn, means that  $V_G$  decreases ( $V_{GS} = V_G - R_{GATE} I_G$ ), thus forcing less current through the tracking FET. This compensates for the initial  $I_G$  increase imagined.

This current regulating effect is even more pronounced if the value of  $R_G$  is high. Ideally, an infinite value resistor would yield a 0% variation in  $I_G$  and, therefore, a 0% variation in the corresponding stage quiescent current.

On the opposite end, no resistor (or a 0 Ohm resistor) has no regulating effect, and the thermal tracking is disabled.

Also note that the resistor temperature variation during the experiment is negligible (less than 0.1%)

Finally, from Tables 1 and 2, note that there is a higher voltage drop through the 4.51 k $\Omega$  than through the 1 k $\Omega$  resistor. This implies the availability of a higher voltage source to better control the quiescent current.

In summary, the constant current regulation is better with a higher value gate resistor, but care is needed to be able to supply the corresponding  $V_G$  voltage (see Figure 7).

A better way to set the quiescent current would be as follows: The ratio  $I_{DQ}/I_G$  is defined by design so gate current

could be used to set individual stage  $I_{DQ}$ 's independently from the part-to-part variation, assuming that everything is perfect.

Table 3 presents the result of a characterization of four different lots. A constant gate current (1.6 mA) has been applied to Stage 3 of MW4IC2020, and the quiescent current is measured. This table shows that with a quite good control of  $I_G$  (1.5% variation), the variation of  $I_{DQ}$  is in the range of 10%. So gate current should not be used to set the individual stage  $I_{DQ}$ 's with good accuracy.

**Table 3.  $I_{DQ}$  versus  $I_G$**

|                    | $I_{G3}$ | $I_{DQ3}$ |
|--------------------|----------|-----------|
| Mean value (mA)    | 1.596    | 204       |
| (Max-Min)/Mean (%) | 1.56     | 9.4       |

The variation of  $I_{DQ}/I_G$  from part to part is because the tracking FET is very small compared to the RF FET so it is more sensitive to the process variation while the RF FET DC characteristic is an average of a large amount of transistor fingers in parallel.

Table 4 presents stage by stage the theoretical ratio RF gate periphery/tracking FET gate periphery.

**Table 4. Ratio of RF FET Size Relative to RF Tracking FET**

|           | Stage 1 | Stage 2 |         |
|-----------|---------|---------|---------|
| MWIC930   | 100     | 400     |         |
| MW4IC915  | 100     | 200     |         |
| MHVIC915  | 50      | 200     |         |
|           | Stage 1 | Stage 2 | Stage 3 |
| MW4IC2020 | 20      | 42      | 100     |
| MW4IC2230 | 20      | 42      | 100     |
| MHVIC2115 | 50      | 100     | 200     |

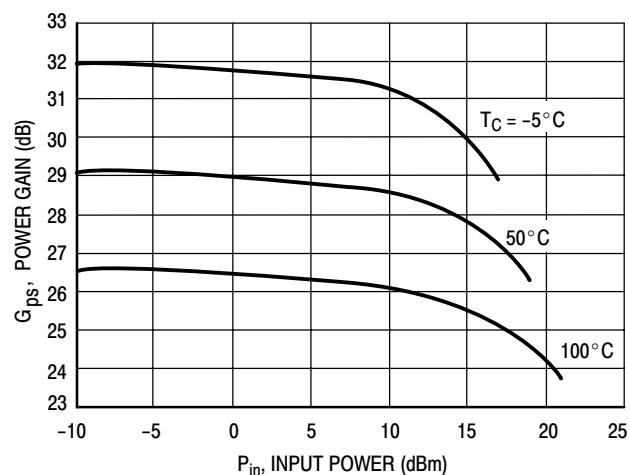
Also, the tracking does not compensate for the HCI (Hot Carrier Injection) that induces  $I_{DQ}$  drift of the power LDMOS. This is because the tracking FET sees a drain voltage of about 4 Volts, which induces negligible HCI. The drain voltage of the power LDMOS is generally comprised between 26 Volts and 32 Volts that induces a certain amount of HCI. If the tracking FET had the same drain voltage as the power FET, HCI tracking would occur in the same manner as thermal tracking.

## LINEARITY PERFORMANCE

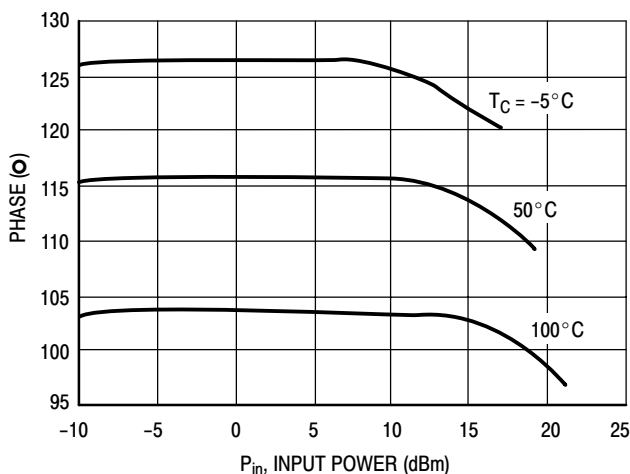
The following set of experiments using the MW4IC2020MB show the RF performances over temperature when the thermal tracking is turned on.

First, the device is evaluated with one tone. AM/AM and linearity performance have been conducted for three temperatures. The bias circuit is made with series resistors  $R_G > 1.5$  kOhms and a voltage power supply. This configuration yields  $\pm 3\%$  quiescent current accuracy over  $150^\circ\text{C}$ . The device is biased at 26 Volts, and  $I_{DQ1} = 80$  mA,  $I_{DQ2} = 200$  mA,  $I_{DQ3} = 300$  mA. Measurement frequency is 1.96 GHz, and tone spacing is 100 kHz for the third order IMD and GSM EDGE signal for the EVM graph.

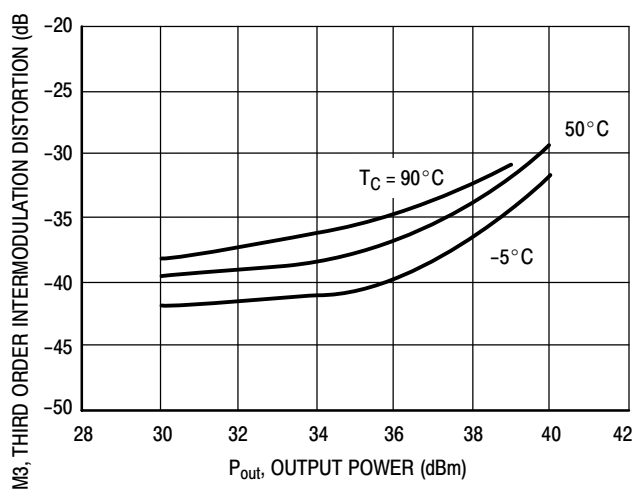
Figures 8 and 9 present the AM/AM and AM/PM versus case temperature. As expected, the shape of the curves are maintained over a large dynamic range. Also, the power capability is degraded due to temperature effect as well as gain.



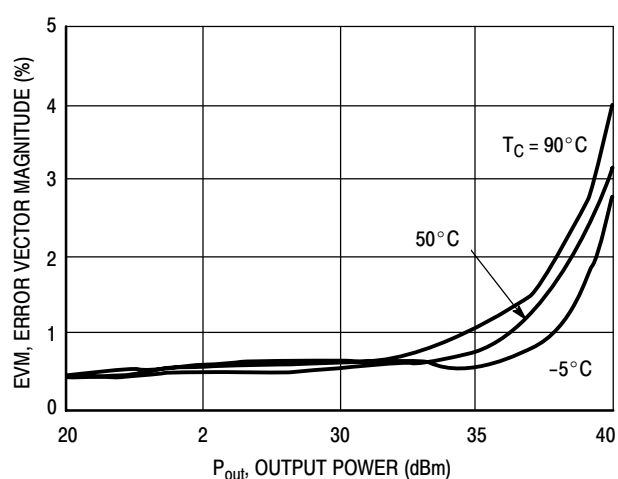
**Figure 8. AM/AM versus Temperature**



**Figure 9. AM/PM versus Temperature**



**Figure 10. Third Order Intermodulation Distortion versus Output Power**



**Figure 11. Error Vector Magnitude versus Output Power**

Figures 10 and 11 present two-tone CW and EDGE performance.

Note the degradation of the power capability of the device when the temperature is increased. Taking into account this effect, the linearity behavior is maintained.

## CONCLUSION

Freescall's new RF power integrated circuits integrate a thermal tracking device that keeps the  $I_{DQ}$  constant for all stages versus temperature variations.

This application note explored the working mechanism of this thermal tracking as well as its performance. Explained

was how with careful resistive loading of the gate bias,  $I_{DQ}$  variations of less than 5% over 100 degrees can be easily obtained. Also described was how to disable the thermal tracking by running a voltage source to the gate bias.

Finally, it showed the RF performance with temperature when the thermal tracking is enabled. As expected, the shape of the different RF parameters remained unchanged over a large dynamic range.

The integrated  $I_{DQ}$  thermal tracking FET is a very useful feature that allows the necessary thermal compensation to be suppressed at the board level.

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