INTRODUCTION

The LDMOS transistors are CMOS devices, designed for high frequency and high power operation. These devices are widely used for RF power amplifier applications such as GSM and CDMA cellular base stations, radar, CATV, and portable radio devices. A limiting factor of these devices is the significant drifts of quiescent current ($I_{DQ}$) at a fixed gate bias voltage ($V_{GS}$) over temperature, due to the charge build-up in the Drain-Gate region, that is caused by hot carrier injection effects.

The $I_{DQ}$ changes proportionally with both the gate bias voltage and temperature.

In order to maintain the maximum output power with high linearity, the $I_{DQ}$ needs to be constant over time across all operating temperature ranges. To achieve this goal, the gate bias voltage needs to be adjusted during operation to compensate the temperature changes.

The Digital-to-Analog Converter (DAC) is favorably used in the bias control circuit for the base station power amplifier module (PAM). In practical applications, the bias control circuit maintains the $I_{DQ}$ within a ±4% range. This application note shows an example of how the Digital-to-Analog (DAC) converter is used for this purpose.

**FIGURE 1:**

(a) Simplified LDMOS RF Power Amplifier with Temperature-Monitored Bias Control Schematics. (b) Typical $I_{DS}$ vs. $V_{GS}$ Characteristics over Temperature.
Figure 1 shows (a) a simplified diagram for the LDMOS bias control using a 12-bit DAC device and a temperature sensor, and (b) a general behavior of $I_{DS}$ vs. $V_{GS}$ over temperature for class AB LDMOS amplifier. At a fixed gate bias voltage ($V_{GS}$), the $I_{DS}$ drifts as temperature changes. Below the zero temperature crossover point (ZTC), $I_{DS}$ is higher with higher temperature. But, above the ZTC point, $I_{DS}$ is higher with lower temperature.

Figure 2 shows the gate bias voltage over temperature for constant quiescent current ($I_{DQ}$), and Figure 3 shows the $I_{DQ}$ over temperature with constant $V_{GS}$.

### BIAS VOLTAGE CONTROL USING DAC

In order to keep $I_{DQ}$ constant over the operating temperature range, the MCU measures the temperature changes using the temperature sensor and sets a new bias voltage, using the 12-bit DAC device. This process can be done by using a look-up table of the $V_{GS}$ value vs. $I_{DS}$ vs. temperature.

![Figure 2: Example of $V_{GS}$ vs. Temperature for Constant $I_{DQ}$](image)

![Figure 3: Example of $I_{DQ}$ vs. Temperature of Typical LDMOS Amplifier with Constant $V_{GS}$](image)

The smallest step size (LSB size) for the bias control voltage depends on the DAC resolution and full scale range. For the 12-bit DAC (MCP4728), the smallest resolution is about 1 mV when the full scale range is set from 0V to 4.096V.

The procedure is summarized below:

a) Pre-store the $I_{DS}$ vs. $V_{GS}$ vs. temperature data in the look-up table in the control device (PIC24 microcontroller).

b) Measure temperature periodically during operation.

c) Control the DAC output voltage for a new $V_{GS}$ voltage using the look-up table.

### Selecting DAC Device

The users have many options in selecting a right DAC device for their specific applications:

- DAC resolutions (8 to 12 bits)
- Accuracy
- Internal or external reference
- Digital interface type
- Number of output channels
- Device cost, etc.

For the cellular base station applications, a 12-bit resolution DAC with multiple channel outputs is suitable. The DAC performance parameters are temperature-dependent, and most of the parameter errors can be corrected using an appropriate algorithm.

### Review of the MCP4728 Features

The MCP4728 is a 4-channel 12-bit voltage output Digital-to-Analog Converter (DAC) from Microchip Technology. Each channel output is individually controlled and can use an internal voltage reference (2.048V) or $V_{DD}$ as reference. Each channel output has an op amp. Therefore, it does not require external output buffers.

The device also has EEPROM memory for each channel. The user can store channel configuration settings in the EEPROM. When the device is first powered up, or recovering from a power failure, the device can immediately provide the same output voltage with the settings in the previous operation. Table 1 summarizes the features of the MCP4728 and Figure 4 shows the functional diagram of the device.
## TABLE 1: KEY PARAMETERS OF MCP4728

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution, N</td>
<td>12 Bits</td>
</tr>
<tr>
<td>Number of output channel</td>
<td>4 Analog Outputs</td>
</tr>
<tr>
<td>Reference Voltage (V_{REF})</td>
<td>The user can select internal or external V_{REF} individually for each channel.</td>
</tr>
<tr>
<td></td>
<td>• If internal reference is selected:</td>
</tr>
<tr>
<td></td>
<td>[ V_{REF} = 2.048\text{V} ]</td>
</tr>
<tr>
<td></td>
<td>• If external reference is selected:</td>
</tr>
<tr>
<td></td>
<td>[ V_{REF} = V_{DD} ]</td>
</tr>
</tbody>
</table>
| LSB (Least Significant Bit)     | LSB is the step size resolution between consecutive DAC inputs. LSB of the MCP4728 is defined as: \[
|                                 | \quad LSB = \frac{V_{REF}}{2^N} G_x \]                                    |
|                                 | = 500 \, \mu\text{V} when Gain = 1x and internal reference is used,        |
|                                 | = 1 \, \text{mV} when Gain = 2x and internal reference is used.            |
|                                 | where G_x is the output op amplifier gain setting.                          |
| Output Voltage                   | The DAC output voltage is defined by the DAC input code, LSB and output op amp gain setting. Its minimum is the offset voltage and the maximum is the reference voltage times the gain setting. The output voltage is given by: \[
|                                 | V_{OUT} = (DAC \, Input \, Code) \cdot (LSB) \cdot (G_x) \]               |
|                                 | \[ DAC \, Input \, Code = \frac{V_{OUT}}{LSB} G_x \]                      |
|                                 | **Example:** Output voltage range                                           |
|                                 | • When internal reference is selected:                                      |
|                                 | \[ V_{OUT} = V_{OFFSET} \text{ to } 2.048\text{V with Gain = 1x setting} \] |
|                                 | = 2 \, V_{OFFSET} \text{ to } 4.096\text{V with Gain = 2x setting}        |
|                                 | • When external reference is selected:                                      |
|                                 | \[ V_{OUT} = V_{OFFSET} \text{ to } V_{DD}, regardless of gain setting \]   |
|                                 | **Note:** When external reference is selected, only gain setting of 1x is used and 2x is ignored. |
| Serial Interface                | **I^2C**<sub>™</sub>                                                       |
|                                 | Three I^2C address bits are stored in EEPROM.                               |
|                                 | • I^2C address bit programming:                                             |
|                                 | (a) The user can reprogram the address bits on the user’s application PCB board by using a simple I^2C address write command, |
|                                 | (b) or the address bits can be pre-programmed for the customer, during the device final testing, at the factory before shipping. |
### Output Settling Time

**Note:** This delay time tells how soon the analog DAC output is settled after the user sends a write command for a new output voltage. This is the time delay between the moment when the DAC input code is loaded to the output DAC register and the DAC analog output has reached the new analog output voltage. Assuming the LDAC pin is grounded, the total delay time for the new output is approximately as follows:

- **Example:** If the user updates the $V_{OUT}$ with the Fast Write command, the output can be updated after the following time delay from the beginning of the Fast Write command:
  - When $I^2C$ clock speed = 3.4 MHz:
    
    \[
    \text{Time delay for } V_{OUT} = 6 \mu s + 8 \times 3 \times \frac{1}{3.4 \text{ MHz}} = 6 \mu s + 7.06 \mu s = 13.06 \mu s
    \]
  - When $I^2C$ clock speed = 400 kHz:
    
    \[
    \text{Time delay for } V_{OUT} = 6 \mu s + 8 \times 3 \times \frac{1}{400 \text{ kHz}} = 6 \mu s + 60 \mu s = 66 \mu s
    \]

### DC Accuracy

**INL**

+/- 2 LSB (typical), +/- 13 LSB (maximum)

**Note:** Integral non-linearity error tells the linearity of the output vs. input code. This INL error can be calibrated.

**DNL**

+/- 0.2 (typical), +/- 0.75 LSB (maximum)

**Note:** Differential non-linearity error tells the difference in output step size as input code change by 1 LSB. The output changes monotonically if the DNL error is less than +/- 1 LSB.

### Output Offset Voltage

5 mV (typical), 20 mV (maximum)

**Note:** The output voltage at code 0x000h is called offset error. For the DAC with output op amplifier, the output offset error is mostly contributed by the op amp's $V_{OS}$ voltage. When the output offset voltage is 5 mV and 1 LSB = 1 mV, the DAC analog output does not change until the input code is greater than 5 LSB. See Figure 5 for more details.

### EEPROM

The device has non-volatile EEPROM memory for the DAC input code, configuration bit settings, and I^2C address bits. The user can reprogram the EEPROM any time. Once the device powers-up, it uploads the EEPROM contents to the output DAC registers. Therefore, the output is immediately available with the programmed data, without help from the MCU. This feature is very useful in the system where accidental power shutdown occurs occasionally. The DAC can provide correct outputs immediately with the previous settings by itself when the power is restored.
FIGURE 4: MCP4728 Functional Block Diagram.
USING THE MCP4728

Figure 5 shows the Output Voltage vs. Digital Input Code of the MCP4728 with the internal $V_{REF}$ and gain of 2x options. The offset voltage ($V_{OFFSET}$ in Figure 5) is a combination of all offsets, including the DAC converter and output op amp. The user must be aware that the output voltage does not increase until the input code exceeds the value for the total offset voltage. This is shown in details in Figure 5.

Figure 6 shows the absolute output error for each channel without corrections. The data is taken only from code 100 to 3500. This represents the 100 mV to 3.5V range. The output voltage error is between 6.5 to 15 LSB (or 6.5 mV to 15 mV) for all 4 channels. The error is mostly due to the offset error which can be easily calibrated. By removing the offset, $V_{OUT}$ will only vary within about 6 LSB or 6 mV. There is a minor variation between channel to channel outputs at the same input code, but the difference is only a few LSBs.

**FIGURE 5:** Output Voltage vs. Code. Note that the $V_{OFFSET}$ is mostly contributed by the $V_{OS}$ of the output amplifier.

**FIGURE 6:** Absolute Output Error of the MCP4728.

Figure 7 shows the MCP4728 external circuit configuration for the applications. Figure 8 shows another example for 8 output channels using two MCP4728 devices.

**I²C Address of the MCP4728**

The device has three reprogrammable I²C address bits. Using the 3 bits, the user can have 8 unique I²C device addresses. The I²C address bits are programmed into the EEPROM before the device is shipped to the customer, and are reprogrammable by the customer. When the user programs the I²C address bits, the LDAC pin is used to select the device for programming. In that case, do not ground the LDAC pin, but connect to the MCU I/O pin as shown in option line in Figure 7 and Figure 8. See the MCP4728 data sheet for more details of the I²C address bit programming options.
**FIGURE 7:** Using the MCP4728 for the Bias Voltage Control Circuit.

**Note:** For more details on the LDAC and RDY/BSY pin functions, see the MCP4728 data sheet, *12-Bit, Quad Digital-to-Analog Converter with EEPROM Memory*, DS22187. The data sheet is available on the Microchip Technology web site, www.microchip.com.
USING THE MCP4728 FOR MORE THAN QUAD OUTPUTS

A typical power amplifier module for the cellular base station has at least 8 to 16 bias voltage control points. Typically, multiple DAC devices are used for these control points.

The MCP4728 has three I²C address bits. The combination of these three bits allows eight distinct addresses. Therefore, the user can connect up to eight MCP4728 devices on the same I²C bus line. By connecting eight devices, 32 DAC channel outputs are available. It needs two MCP4728 devices for octal outputs, and four MCP4728 devices for 16 outputs.

Figure 8 shows an example of using two MCP4728 devices for octal outputs.

The LDAC pin in the MCP4728 is used for two purposes: (a) Loading the DAC input registers to the output registers synchronously and (b) Device selection input when reprogramming I²C address bits at the user’s application PCB board. If the above are not needed, then the user can simply ground the LDAC pin instead of connecting it to the MCU. In this case, the output of each channel will be updated whenever the DAC input register is updated by the user’s write command.

**Figure 8:** Using the MCP4728 for Octal Outputs.

**Note:** The user can connect up to eight MCP4728 devices on the same I²C Bus line.

R1 and R2 = Pull-up resistors for SCL and SDA, respectively

- 5 kΩ - 10 kΩ for fSCL = 100 kHz to 400 kHz
- ~700 kΩ for fSCL = 3.4 MHz

C1: 0.1 µF, Ceramic capacitor
C2: 10 µF, Tantalum capacitor
CONCLUSION

There are many ways to design a bias voltage control circuit for the LDMOS power amplifier. One of the most effective solutions is using a stand-alone DAC and a temperature sensor. The MCP4728, a 12-bit voltage output DAC, is suitable for the LDMOS bias voltage control applications. The device provides stable and consistent performance over the wide temperature range from -40°C to +125°C. Multiple MCP4728 devices can be connected to the same I²C bus line if an application needs more than 4 independent control voltages.

Note: Microchip will continuously release new DAC devices for multiple output channels with SPI and I²C serial interface options. Please contact the Microchip office near you for further update of the product availability.

REFERENCES

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.

- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.

- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip's Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.

- Microchip is willing to work with the customer who is concerned about the integrity of their code.

- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as "unbreakable."

Code protection is constantly evolving. We at Microchip are committed to continuously improving the code protection features of our products. Attempts to break Microchip's code protection feature may be a violation of the Digital Millennium Copyright Act. If such acts allow unauthorized access to your software or other copyrighted work, you may have a right to sue for relief under that Act.

Information contained in this publication regarding device applications and the like is provided only for your convenience and may be superseded by updates. It is your responsibility to ensure that your application meets with your specifications. MICROCHIP MAKES NO REPRESENTATIONS OR WARRANTIES OF ANY KIND WHETHER EXPRESS OR IMPLIED, WRITTEN OR ORAL, STATUTORY OR OTHERWISE, RELATED TO THE INFORMATION, INCLUDING BUT NOT LIMITED TO ITS CONDITION, QUALITY, PERFORMANCE, MERCHANTABILITY OR FITNESS FOR PURPOSE. Microchip disclaims all liability arising from this information and its use. Use of Microchip devices in life support and/or safety applications is entirely at the buyer's risk, and the buyer agrees to defend, indemnify and hold harmless Microchip from any and all damages, claims, suits, or expenses resulting from such use. No licenses are conveyed, implicitly or otherwise, under any Microchip intellectual property rights.

Trademarks

The Microchip name and logo, the Microchip logo, dsPIC, KEELOG, KEELOG logo, MPLAB, PIC, PICmicro, PICSTART, PIC 32 logo, rPIC and Uni/O are registered trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.

FilterLab, Hampshire, HI-TECH C, Linear Active Thermistor, MXDEV, MXLAB, SEEVAL and The Embedded Control Solutions Company are registered trademarks of Microchip Technology Incorporated in the U.S.A.

Analog-for-the-Digital Age, Application Maestro, CodeGuard, dsPICDEM, dsPICDEM.net, dsPICworks, dsSPEAK, ECAN, ECONOMONITOR, FanSense, HI-TIDE, In-Circuit Serial Programming, ICSP, Mindi, MiWi, MPASM, MPLAB Certified logo, MPLIB, MPLINK, mTouch, Octopus, Omniscient Code Generation, PICC, PICC-18, PICDEM, PICDEM.net, PICKit, PICtail, REAL ICE, rLAB, Select Mode, Total Endurance, TSHARC, UniWinDriver, WiperLock and ZENA are trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.

SQTP is a service mark of Microchip Technology Incorporated in the U.S.A.

All other trademarks mentioned herein are property of their respective companies.

© 2010, Microchip Technology Incorporated, Printed in the U.S.A., All Rights Reserved.

Printed on recycled paper.

ISBN: 978-1-60932-265-6

Microchip received ISO/TS-16949:2002 certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona; Gresham, Oregon and design centers in California and India. The Company's quality system processes and procedures are for its PIC® MCUs and dsPIC® DSCs, KeeLoq® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip’s quality system for the design and manufacture of development systems is ISO 9001:2000 certified.