

TABLE OF CONTENTS

TABLE OF CONTENTS..... 2

REVISION HISTORY 3

SPECIFICATIONS 4

 Environmental Specifications..... 4

 Internal Temperature Sensor Specifications..... 4

 Thermal Controller Specifications..... 4

 Data Converter Specifications..... 5

 Oscillator Specifications 5

 Output Specifications..... 5

 Digital Clock Specifications..... 5

 Absolute Maximum Ratings 6

PIN CONFIGURATION AND FUNCTION..... 7

BLOCK DESCRIPTION & FUNCTIONALITY..... 9

 Oscillator Stage 9

 RF Output Stage 11

 Thermal Controller..... 12

 Internal Heaters 17

 External Heaters..... 18

 Correction System..... 19

 Internal Temperature Sensor..... 19

 Analog to Digital Converter & MUX 20

 Power Domains 20

 Microcontroller & Memory..... 21

 Microcontroller Clock Source..... 22

OCXO TEMPERATURE CORRECTION ALGORITHM OVERVIEW 23

 Adjustable Timing Parameters..... 24

 Lookup Table Curve Fit..... 24

 Temperature Correction Polynomial Curve Fit 25

 Supply Voltage Curve Fit..... 26

 Correction Algorithm Implementation 27

APPLICATION NOTES..... 28

 Oscillator Power Supply Options..... 28

Internal Pierce Oscillator Properties 30

Disabling Pierce Oscillator..... 35

Output Signal Architecture Options..... 36

HThRM NTC Thermistor Usage..... 38

HThRM Thermal Controller Temperature Set Point Example 39

External Thermal Range Resistor 41

Cavity Temperature Measurement..... 42

Thermal Time Constants 42

Allan Deviation (Allan Variance) 43

MCU Clock Source Selection 44

External Thermistor (ThRM Pin) 44

DESIGN EXAMPLE..... 46

 Oscillator 46

 OCXO Module..... 47

 Phase Noise Performance 48

 Frequency Stability..... 49

 Other Design Examples 49

PCB CONSIDERATIONS 50

 Power Supply Filtering 50

 Signal Traces..... 50

DIE & PAD COORDINATES 51

DIE Bonding Guidance..... 53

Package Outline 54

REVISION HISTORY

Revision	Date	Description
1.0	01/2023	Initial Release
1.1	06/2023	Corrections and updates

SPECIFICATIONS

Environmental Specifications

Table 1 Recommended Operating Conditions

Parameter	Conditions	Min	Typ	Max	Unit
Supply Voltage	± 5%	3.135	3.3	3.465	V
Operating Temperature		-40		125	°C
OTP Programming Temperature		0		50	°C

Internal Temperature Sensor Specifications

Table 2 Temperature Sensor Specifications

Parameter	Conditions	Min	Typ	Max	Unit
Absolute Accuracy		-0.25		0.25	°C
Voltage Range	-40C to 125C	1.32		2.5	V
Resolution	ADC LSB		0.11		°C
Linearity	-40C to 125C		0.6		%
	70C to 125C		0.2		

Thermal Controller Specifications

Table 3 Thermal Controller Specifications

Parameter	Conditions	Min	Typ	Max	Unit
Internal Heater Current	-40C	160		267	mA
	100C	160		221	
	125C	160		211	
Continuous Internal Heater Power	3.3V Supply (VDDHx)			0.5775	W
Thermal Controller Output Drive Range	Internal Heater	0		Vdda - 0.1	V
	External Heater	0		Vdda - 0.1	
Max Thermal Controller Drive Current	External Heater	7	8.1		mA
Thermal Controller Feedback Range	Internal Heater	0	0.653	0.782	V
	External Heater	0	1.5		
Current Limiting DAC Reference			2.9		V
Current Limiting DAC Resolution			7		bits
Current Limiting DAC Codes			128		steps
Current Limiting DAC LSB			22.7		mV
Temp Set Point Range	Internal resistor network	70		110	°C
	External resistor network	-20		110	
Temp Set Point Resolution	12-bit resolution			0.04	°C

Data Converter Specifications

Table 4 Correction DAC DC Specifications

Parameter	Conditions	Min	Typ	Max	Unit
Temperature Range		-40	27	125	°C
Monotonicity		12			Bits
Resolution		12			Bits
Least Significant Bit	BYPASS = 2.9V		0.708		mV
Differential Non-Linearity		-1	±0.5	+1	LSB
Integral Non-Linearity		-4	± 2	+4	LSB
Output Range	BYPASS = 2.9V	0.3		2.9	V

Oscillator Specifications

Table 5 Oscillator Specifications

Description	Conditions	Min	Typ	Max	Unit
Input Frequency	Internal CA/CB capacitors only	5 ¹		155	MHz
CA Range	Adjustable	2		52	pF
CB Range	Adjustable	2		62	pF
RD Range	Adjustable	25		1000	Ω
RF Range	Adjustable	1.6k		100k	Ω
Duty Cycle	Adjustable	45	50	55	%

¹ Using external capacitors allows for operation below 5MHz

Output Specifications

Table 6 Output Stage Specifications

Parameter	Conditions	Min	Typ	Max	Unit
Maximum Output Frequency	15pF load		200		MHz
	50pF load		100		
Rise/Fall Time (10%-90%) of VDDA	8mA drive - 15pF Load		2.0		ns
	8mA drive - 50pF Load		4.8		
	4mA drive - 15pF Load		3.7		
	4mA drive - 50pF Load		9.1		

Digital Clock Specifications

Table 7 Processor Clock Frequency

Parameter	Conditions	Min	Typ	Max	Unit
Internal Ring Oscillator Frequency			10		MHz
Processor Clock Frequency		1		10	MHz
OTP Read Temperature		-40		125	°C
OTP Programming Temperature	Set VDDA to 3.465V for best results	0		50	°C
OTP Memory Size			32k		Bytes
ROM Memory Size			3k		Bytes
RAM Memory Size			1k		Bytes

Absolute Maximum Ratings

Table 8 Absolute Maximum Ratings

Parameter	Conditions	Min	Max	Unit
Supply Voltage		0.5	3.8	V
Pin Voltage	EN	-0.5	5.5	V
	SCL	-0.5	5.5	
	SDA	-0.5	5.5	
	All Other Pins	-0.5	3.8	
Soldering Temperature			260	°C
Storage Temperature		-55	150	°C
Junction Temperature			150	°C
ESD Ratings	Human Body Model (HBM)	2000		V
	Machine Model (MM)	100		
	Charged Device Model (CDM)	1000		

PIN CONFIGURATION AND FUNCTION

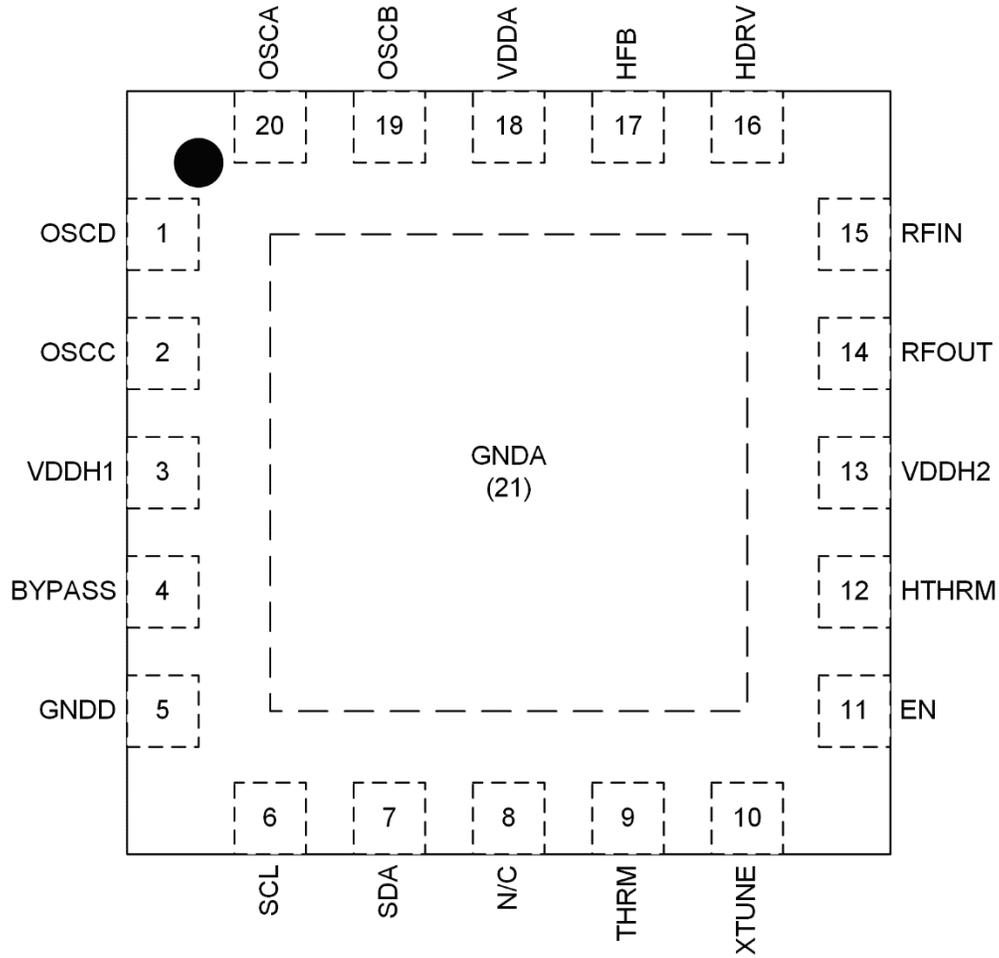


Figure 1 TM200 Package Pinout

Table 9 TM200 Pinout

Pin	Name	I/O/P	Description
1	OSCD	I/O	Crystal drive when internal Varicap is used.
2	OSCC	I/O	Crystal drive when internal Varicap is bypassed and not used.
3	VDDH1	P	3.3V Internal Heater supply. The current on this pin can be up to 175mA.
4	BYPASS	I/O	Internal oscillator power supply. Will require either 22uF/0.01uF bypass capacitors or 1nF compensation capacitor depending on configuration.
5	GNDD	P	Digital ground
6	SCL	I/O	Tuning (EFC) & I ² C interface input clock. An external pullup resistor to VDDA of 10kΩ is needed during I ² C communications. The pin contains an internal pull-down resistor of 110 kΩ. 5V tolerant.
7	SDA	I/O	Open drain serial data input/output for the I ² C interface. An external pullup resistor to VDDA of 10kΩ is needed during I ² C communications. The pin contains a high value internal pull-down resistor. 5V tolerant.
8	N/C	n/a	Not connected
9	THRM	I	External NTC thermistor input. Use this input to use an external thermistor as an alternative crystal measurement method than the internal IC temperature sensor.
10	XTUNE	I/O	External Tuning Voltage. The pin is driven by the output of the Correction DAC and/or the EFC input. It typically controls the voltage on a varactor. It is not connected when the Correction block is configured to drive the internal Varicap.
11	EN	I/O	Enable signal. The polarity and default state is programmable through the internal processor. 5V tolerant.
12	HTRM	I/O	Thermal Controller thermistor terminal. This pin is used to connect an NTC thermistor required to close the feedback loop of the Thermal Controller.
13	VDDH2	P	3.3V Internal Heater supply. The current on this pin can be up to 175mA.
14	RFOUT	O	RF Output. The RFOUT pin provides a CMOS output signal with properties defined in the output stage section.
15	RFIN	I	RF Input. RFIN is the input receiver connection from the oscillator stage output. It is usually driven via a capacitor from OSCB.
16	HDRV	O	External Heater Drive. This is used only when external heaters are being implemented and needs to be configured to drive either NMOS or NPN heater transistors and can drive up to 9mA
17	HFB	I	External Heater Feedback. Voltage signal connected to the load resistors of the external heaters that provides feedback to the thermal controller.
18	VDDA	P	3.3V Analog positive supply. The current on this pin can be up to 30mA.
19	OSCB	I/O	Pierce inverter state output. This signal is usually fed to RFIN via a series capacitance to provide a drive to the output stages.
20	OSCA	I/O	Pierce inverter stage input from crystal.
21	GNDA	P	Analog ground

BLOCK DESCRIPTION & FUNCTIONALITY

Oscillator Stage

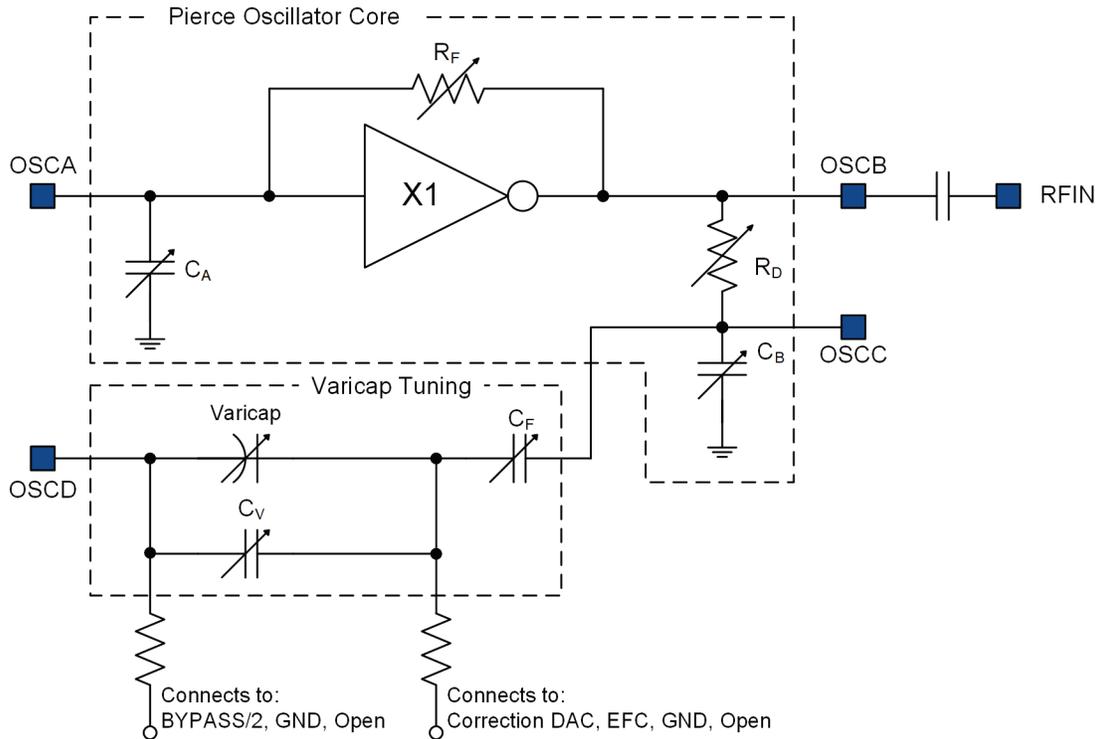


Figure 2 Oscillator Stage Architecture

Pierce Oscillator Core

The oscillator uses a Pierce architecture, designed to be compatible with fundamental or overtone AT cut crystals and overtone SC cut crystals up to 156MHz. It includes an embedded inverter with adjustable resistors and capacitors. The gain stage (X1) is an optimized P/N FET inverter pair. The values for C_A , C_B , C_F , C_V , R_F , and R_D are set using the control registers and are easily configured with the TMx00 Control Software. The oscillator stage is powered through the BYPASS pin and can be shorted to the VDDA pin of the IC or decoupled from VDDA by configuring an internally 2.9V regulator to drive the BYPASS pin. See the Application Notes more information.

Most oscillator applications can be met with the internal component value selections, thereby reducing the amount external components needed to construct an oscillator. Alternatively, the R_F and R_D select logic allows disabling the internal resistors for use with external components. C_A and C_B capacitors can be fully disabled especially for applications with matching and trap networks in series with overtone crystals. When the C_A and C_B capacitors are disabled, the minimum capacitance is $\sim 2\text{pF}$.

Oscillator Connections

OSCA is the Pierce inverter input, typically connected to one side of the crystal. OSCB is the Pierce inverter output used to feed an output stage. OSCA and OSCD are the crystal connections for applications that use the internal Varicap. A blocking cap is necessary between OSCC or OSCD and the crystal to prevent DC bias across the crystal. For applications that use an external varactor, the other side of the crystal is connected to OSCC and OSCD is left open.

Please refer to the *TMx00 Design Example Manual* for examples of various oscillator architectures that can be built with the TM200.

Internal Varicap Tuning

The internal Varicap, C_V , and C_F provide internal voltage controlled tunability. The internal Varicap is a MOS device that has a variable capacitance value that varies with the DC voltage applied via the two control points shown in Figure 2. C_V controls the capacitance range of the Varicap. C_F is a series capacitor that can also tune the Varicap operation.

The Internal Varicap capacitance can be varied between 9pF to 34pF depending on the bias condition across the device. Referring to Figure 2, the left-hand terminal of the Varicap is set to the BYPASS/2 voltage when in operation (A GND or OPEN connection is made when an external varactor is used). The right-hand side of the Varicap can be driven from the Correction DAC or EFC pin (A GND or OPEN connection is made when an external varactor is used).

When the voltage applied to the right-hand terminal is at BYPASS voltage, the Varicap capacitance is set to the minimum value of 9pF. Conversely, when the right-hand terminal is 0V, the Varicap capacitance is set to the maximum value of 34pF.

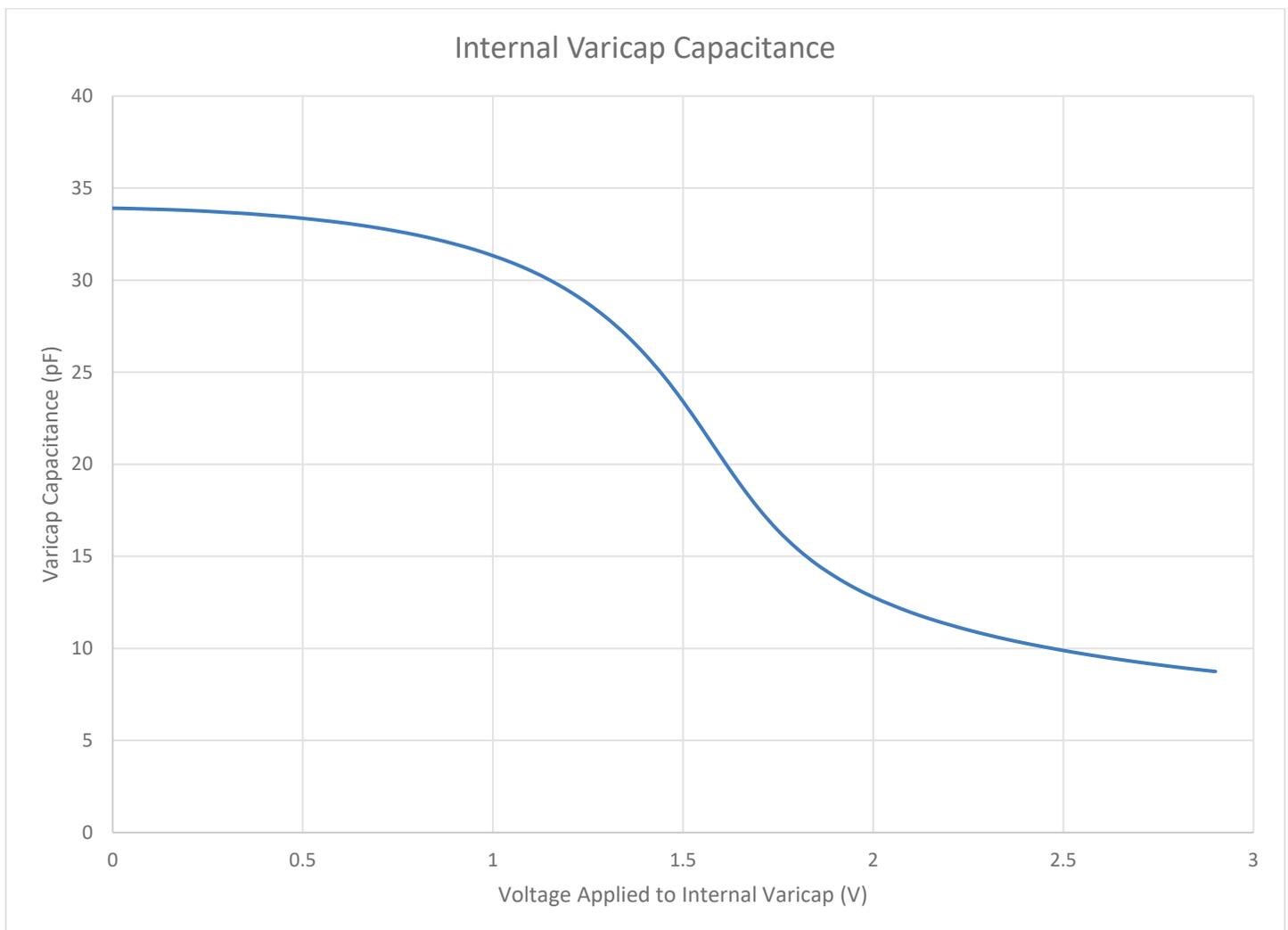


Figure 3 Internal Varicap Capacitance Curve

RF Output Stage

The TM200 includes an RF Output Stage block that conditions the RF output waveform of the oscillator signal, usually driven by a capacitor from OSCB. It restores the clock edges, makes duty cycle adjustments, and performs any necessary clock division before driving the output load. The block also detects the presence or absence of an oscillator input signal (RFIN) and buffers the clock signal for use as an internal microprocessor clock.

Clock frequency divisions of 1, 2, 4 and 8 are available. The CMOS clock driver has a 4mA/8mA drive current setting that allows the user to select the appropriate drive characteristics for a given output load.

An enable function under the control of the MCU allows tri-state output.

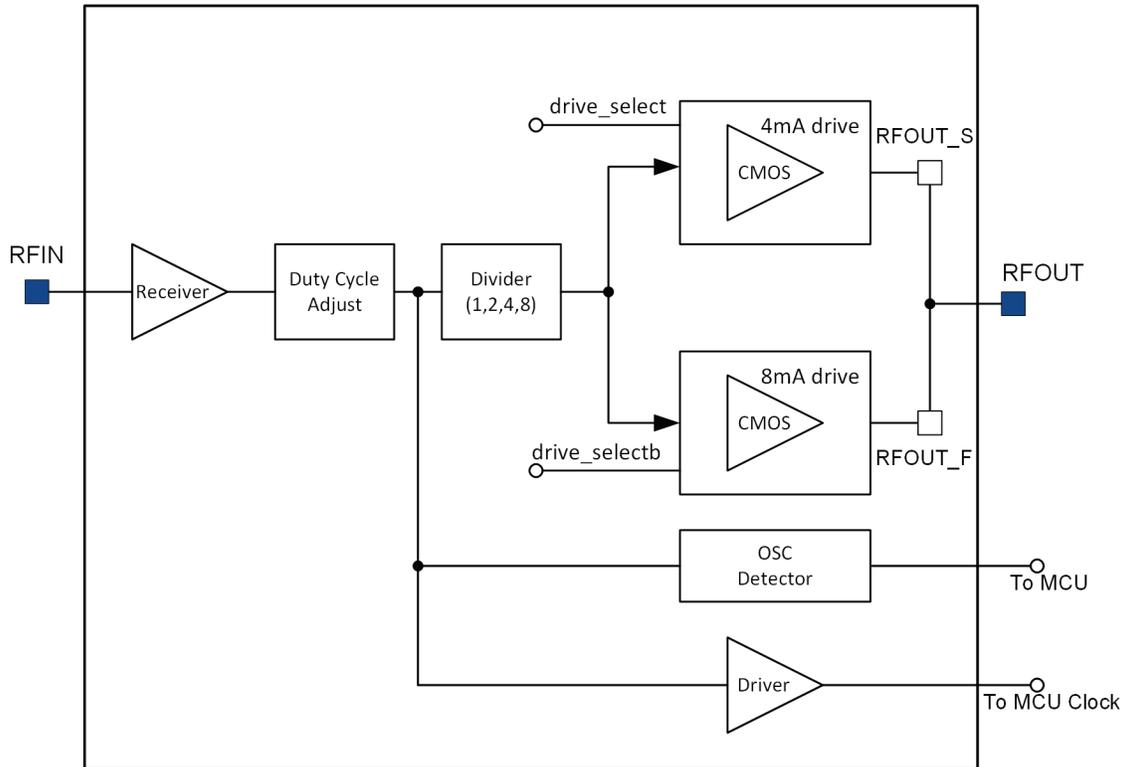


Figure 4 RF Output Stage Architecture

Using the RF Output Stage is not required to produce an output waveform. An unbuffered inverter driven from RFIN is an alternative signal path that may produce a lower phase noise floor. Additional information regarding the output signal generation is described in the Application Notes section.

Thermal Controller

The Thermal Controller is used to control the thermal characteristics of an enclosed module or section of an assembly. It was specifically designed to implement an *oven-controlled crystal oscillator (OCXO)* with low Allan deviation but can be used to construct other thermal application designs. For an OCXO design, the thermally controlled section encloses the crystal resonator in a temperature-controlled region.

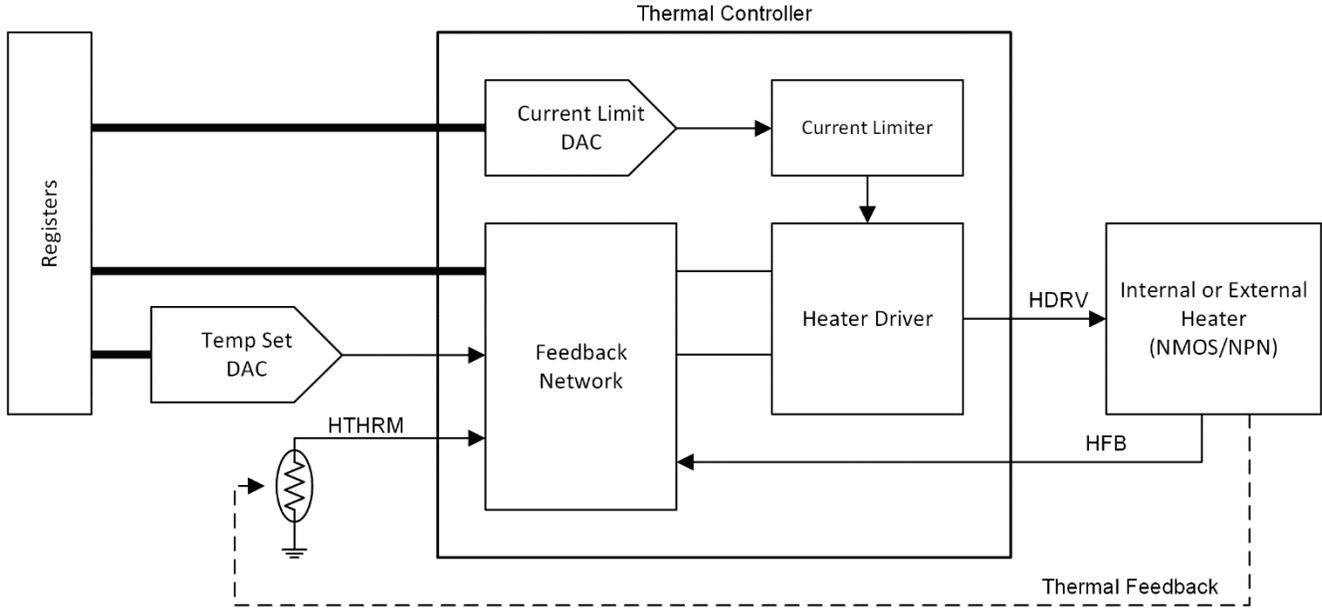


Figure 5 Thermal Controller Architecture

The Thermal Controller uses a driver to control a heater circuit that dissipates heats and causes the cavity temperature to rise. When it is initially turned on, the controller produces more heat until the cavity temperature stabilizes. During this warmup period, the Current Limit DAC & Limiter limits the maximum supply current. After the warmup period, proportional control allows the cavity to remain at the desired temperature via an external thermistor. Heater power provides a data input into the feedback network to adjust and stabilize the cavity temperature. The Temp Set DAC allows for fine grained temperature control managed by the TM200 MCU.

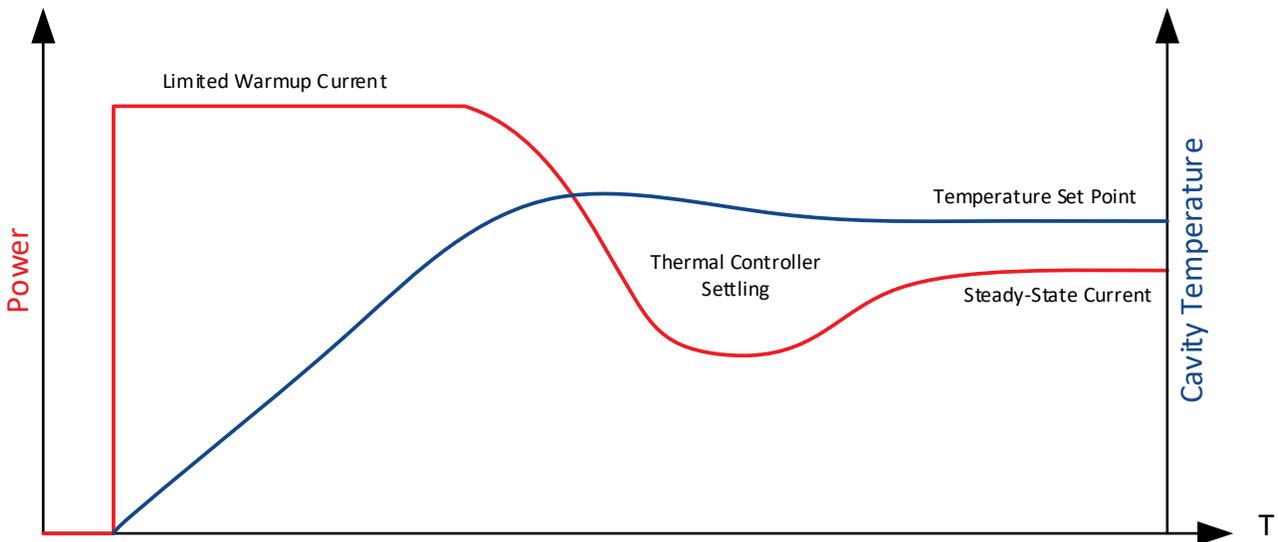


Figure 6 Thermal Controller Current & Cavity Temperature

Heater Driver

The heater driver is a circuit that drives either NMOS or NPN transistors of heater structures. It is designed to deliver the appropriate current for the transistors through the HDRV pin to achieve the desired thermal output. Two different drive levels available, one for FET transistors and one for Bipolar transistors. The FET mode can drive up to 500uA sourcing, and the Bipolar mode can drive up to 7mA (worst case, -40C). 7mA is sufficient typically for 4 Bipolar NPN transistors loaded into 2Ω resistors, for a large cavity of at least 30mm x 30mm.

In the case of using the TM200 internal heaters, the heater driver needs to be configured for the FET level of drive current and the HDRV pin is not connected externally as the connection is already made internally within the IC.

Current Limit DAC & Current Limiter

Upon startup, the Thermal Controller heater driver will produce more heat until the crystal resonator (for an OCXO application) temperature stabilizes (warmup period). The Current Limiter is used to limit the maximum operation current during this warmup period. (Proportional control allows the cavity to remain at the desired temperature after the warmup period.) This is useful to prevent any unintended power-up in-rush current timing, thermal runaway conditions, and long-term reliability.

A 7-bit Current Limit DAC sets the maximum current the heater will deliver by setting the trip point of the comparator. When the heater power is applied and the cavity temperature is low, the heater current and the resulting HFB voltage increases until the comparator trips. Once tripped, the driver limits the heater current and thus the overall current dissipation of the heaters. The appropriate voltage trip value is dependent on the heater network and the full-scale voltage of HFB.

In the case of using the TM200 internal heaters, the HDRV & HFB pins are not connected externally as the connection is already made internally within the IC.

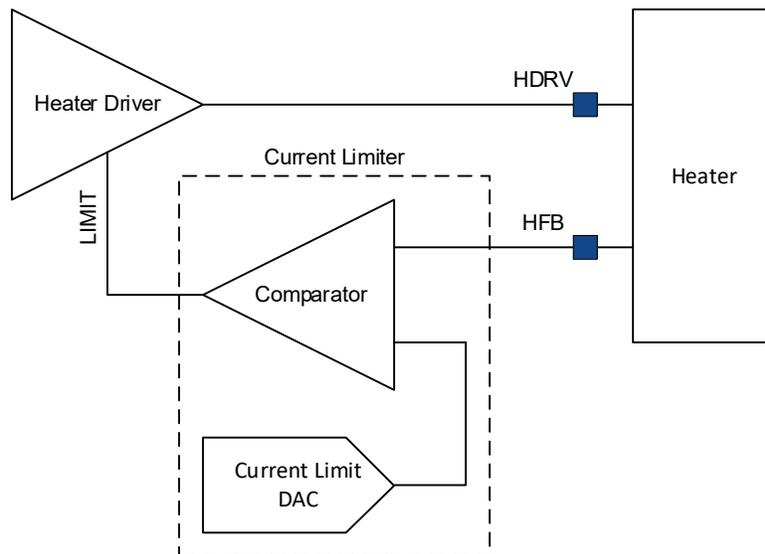


Figure 7 Current Limiter

Feedback Network

The feedback network is an input bridge consisting of R1, R2, feedback resistors R5 & R6, and the Thermal Range Resistor R3. R1 and R2 shift the feedback bias voltage up to a mid-point level for easy comparison to the thermistor voltage. The feedback resistors R5 & R6 monitor the voltage across the heater resistors (through HFB), indicating the power provided to the heated thermal environment. The NTC thermistor provides the necessary thermal feedback.

When the two voltage inputs of the driver circuit are equal, the bridge is in balance and the controlled temperature is held at that point. Balance occurs when $V+$ and $V-$ are approximately $V_{BYPASS}/2$, with the series connection of R1/R2/R6. HFB is the current sense input that provides a slight perturbation of the balance point. This analysis assumes the Temp Set DAC is $V_{BYPASS}/2$ resulting in no current through R4. Moving the Temp Set DAC output voltage into R4 produces a current used to make fine grain temperature adjustments. The TMx00 Control Software provides an estimate of the temperature set point.

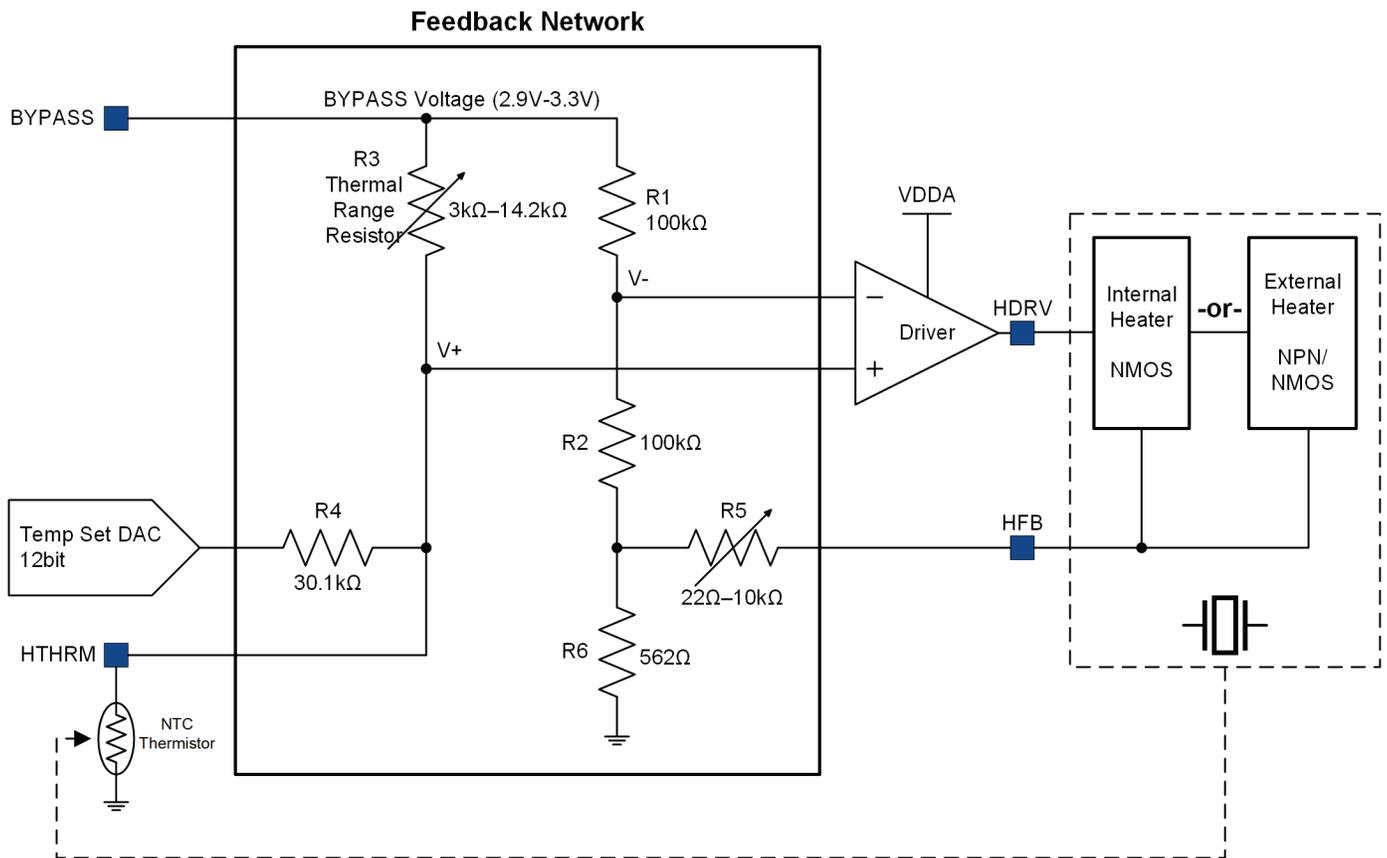


Figure 8 Thermal Controller Feedback Network

Temperature Set Point

Determining the Thermal Controller’s temperature set point is a function of three circuit elements.

- NTC Thermistor
- Thermal Range Resistor (R3) – Coarse temperature set point adjustment
- Temp Set DAC – Fine temperature set point adjustment

The TM200 is primarily designed to work with a negative temperature coefficient (NTC) thermistor that has a 100kΩ resistance value at room temperature. The temperature set point is coarsely determined by setting the Thermal Range Resistor (R3) equal to the resistance of the NTC thermistor at the desired temperature. Assuming the Temp Set DAC output voltage is $V_{BYPASS}/2$, this balances the feedback network legs at the desired temperature. The temperature set point is

finely adjusted with the Temp Set DAC output voltage which provides a trim current through R4. The R3 values and the range of the Temp Set DAC are designed to have overlapping temperature ranges eliminating gaps in the temperature set point.

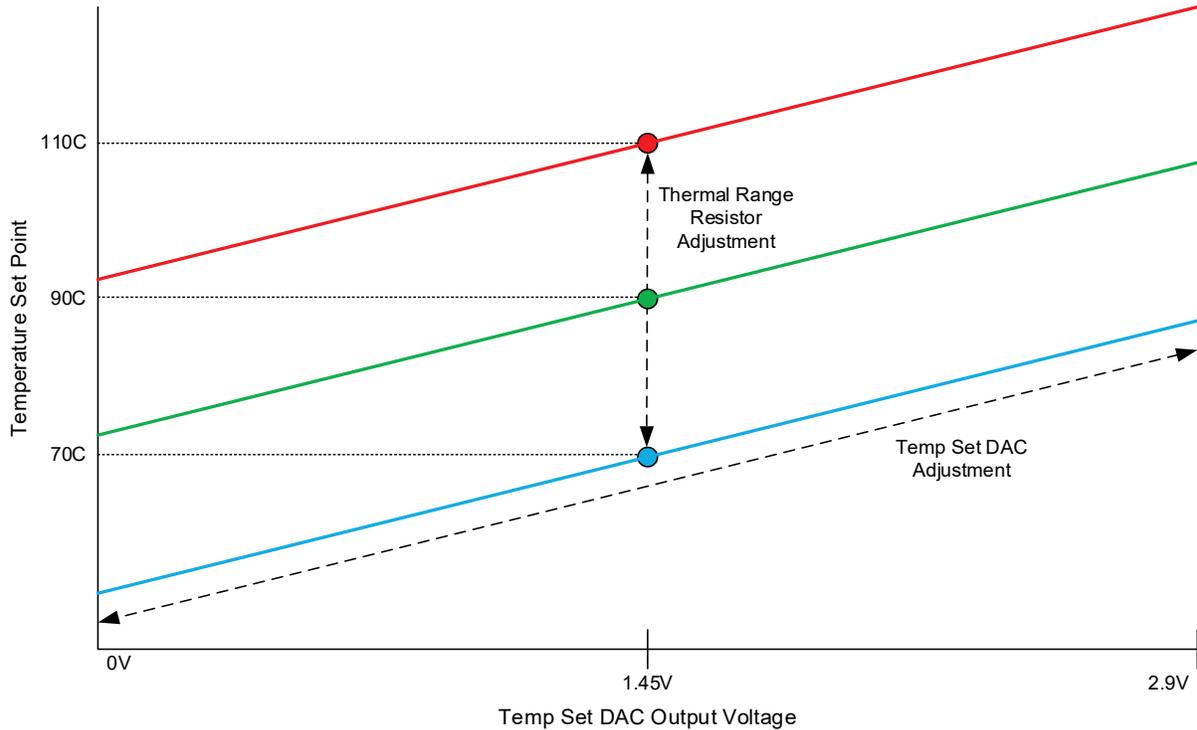


Figure 9 Approximate Temperature Set Point Ranges

Thermal Range Resistor (R3) Structure

R3 is constructed with two banks of resistor values. Only one of the resistors in the first bank may be selected (or all resistors OPEN). Any of the resistors in the second bank may be selected in parallel with the first bank or individually to determine the R3 value. The defined values of the resistors are approximate because of IC process variation. Using the R3 internal values provides a temperature set point range of approximately 70C and 110C. This range matches many OXCO applications.

Using an external Thermal Range resistor supports extended temperature range operation. In some applications the external resistor may result in tighter thermal control of the cavity. Additional details and examples on using an external resistor, NTC thermistor, Thermal Range Resistor (R3) and the Temp Set DAC to set the temperature set point are described in the Application Notes section.

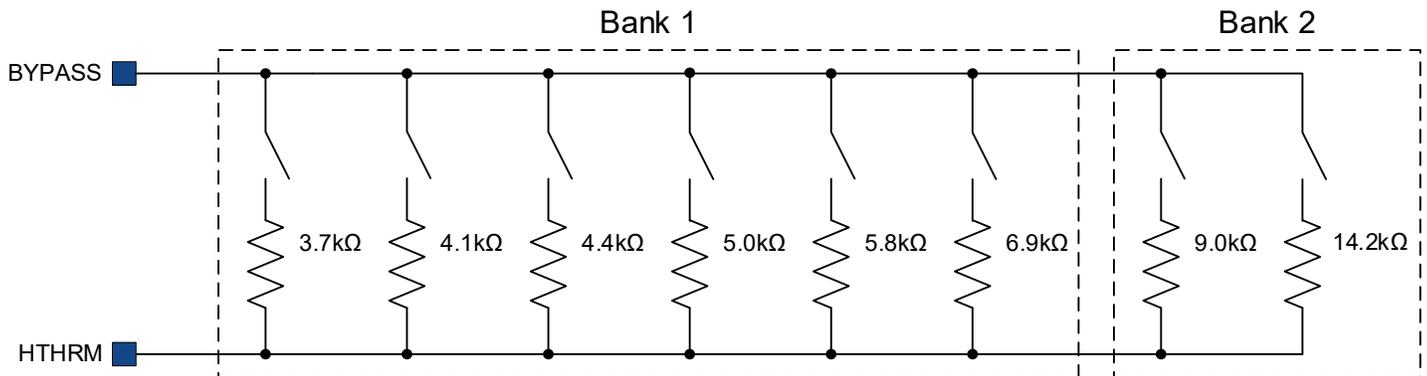


Figure 10 Coarse Temp Set Resistor Structure

Thermal Feedback

The thermal control circuitry is stable with excellent phase margin based on the built-in compensation network for internal heater applications. The value of resistor R5 is selected for optimum thermal settling time without excessive overshoot. The internal compensation assumes current feedback in addition to thermal feedback. No external components are needed, except for a possible snubber network on the HDRV in some external drive scenarios (Figure 12).

Controlling the internal heaters in conjunction with external heaters is not supported as the loop stability dynamics can be significantly different. This is especially the case between NMOS and NPN transistors.

The TM200 firmware also supports a delay time from power on to the time at which the heater power is enabled. It also supports soft start that ramps the current limit from 0 to the desired limit value over a defined time.

MCU Thermal Controller Inputs

The HFB, THRM, and internal temperature sensor signals are digitized under program control and fed to the MCU through the common ADC. The resulting data can be used for diagnostics, algorithm adjustments, and related purposes.

Internal Heaters

Two nominal 0.565W heating elements are used to produce a minimum 1W of total output power at -40 degrees with a 3.3V supply. The heaters are composed of NMOS FET devices in source follower configurations with a resistive load as the heating element. The heater transistors and resistors tightly couple to the center bottom pad of the TM200. Heat from the transistors and resistors combine as the thermal source for the oven cavity.

Each heater contains 4 current legs, one of which includes an HFB terminal that swings roughly between 0V to 0.7V as the HDRV terminal swings between 0V to 3.3V. The power should be limited to 1W total for long term reliability which corresponds to an HFB voltage of approximately 0.5V

HDRV and HFB are controlled and sensed, respectively, by the Thermal Controller. *No external connections to those pins are necessary when the internal heaters are used.* If more than 1W of power output is desired, an external heater structure must be used (see next section). The TM200 does not support using internal and external heaters simultaneously because the IC is not capable of stabilizing two thermal loops.

Heater 1 is supplied by the VDDH1 pin and Heater 2 is supplied by VDDH2. VDDH1 and VDDH2 are connected externally and 175mA of current can flow through each of these pins. Metal routing outside of the IC needs to be sized accordingly.

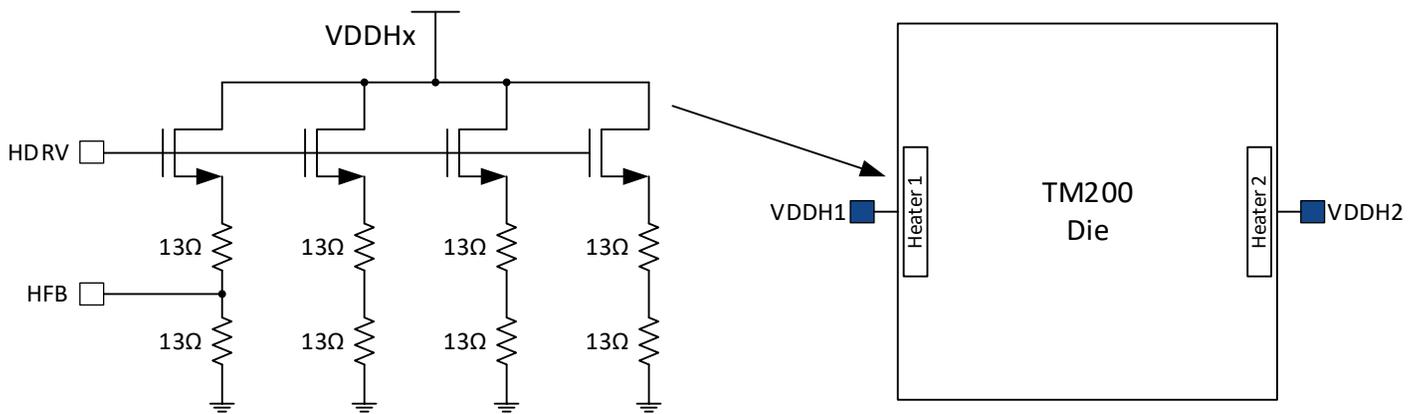


Figure 11 Internal Heater Structure

Current Restriction

Due to resistor value variation that occurs during manufacturing, the IC is often capable of producing a power output beyond the safe operating limits. To maintain long term reliability, the total continuous power output must be limited with the current limiting setting in the Thermal Controller.

Table 10 Individual Heater Output Variation

	Min	Typ	Max	Unit
HFB range	457.6	617.3	733.3	mV
Power @ -40	501.6		742.9	mW
Power @ 100	501.6		618.4	mW
Power @ 125	501.6		591.8	mW

The resistance of the internal heater feedback resistor is measured during production testing and stored in the IC's memory. Reading this value from memory is required to programming the correct current limit setting.

External Heaters

An external heater structure can be controlled by the Thermal Controller through the HDRV and HFB pins. If more than 1W of power output is desired, external heater elements must be used. The TM200 does not support using internal and external heaters simultaneously because the IC is not capable of stabilizing two thermal loops.

Either NMOS FETs or NPN bipolar transistors can be used for external heaters. PMOS and PNP transistors are not supported. FETs require very little gate drive from the HDRV pin, while bipolar power transistors need a base drive of $1/(\text{transistor } \beta)$. The maximum available drive is a programmable option of the Thermal Controller heater driver set to either 500 μ A maximum for FETs or 7mA maximum for bipolar transistors. The 7mA maximum output supports up to 4 high β bipolar power transistors that can drive thermal enclosures approximately 30mm x 30mm.

Bipolar heaters may need equalizing resistors on each device base to avoid current hogging in which one device handles most of the overall heater current. The resistors improve the balance between devices ensuring that one leg does not attempt to provide all the current needed.

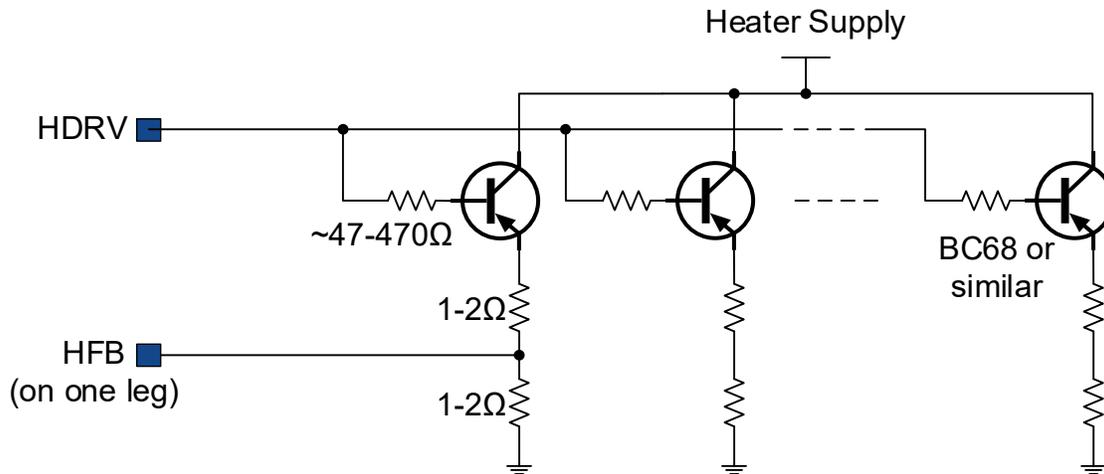


Figure 12 External Bipolar Heater Example

Correction System

The correction system is designed to correct the frequency shifts of a crystal across temperature with either the TM200’s internal Varicap or an external varactor. Using the ADC to convert temperature sensor data, the MCU provides the input code to a 12-bit DAC with an output voltage that adjusts the internal Varicap or external varactor to corrects crystal frequency variation across a defined temperature range. For OXCO applications, the range will likely be limited around the turnover point of the crystal since the module is designed to have the cavity operate at a constant temperature.

The correction system uses either the internal Varicap or an external varactor to provide the appropriate crystal pull. The internal Varicap is suitable for low-cost designs that require minimal components. For higher performance requirements, an external varactor may be used and controlled with the XTUNE pin. Please refer to the Design Examples for more information.

The internal Varicap or XTUNE pin can also be controlled from the dual use SCL (EFC) pin via an analog connection. Alternately the EFC and MUX pins can be used as an input to the ADC. The digitized value is processed in the MCU via correction algorithms and fed out via the correction DAC to control the Varicap or external varactor.

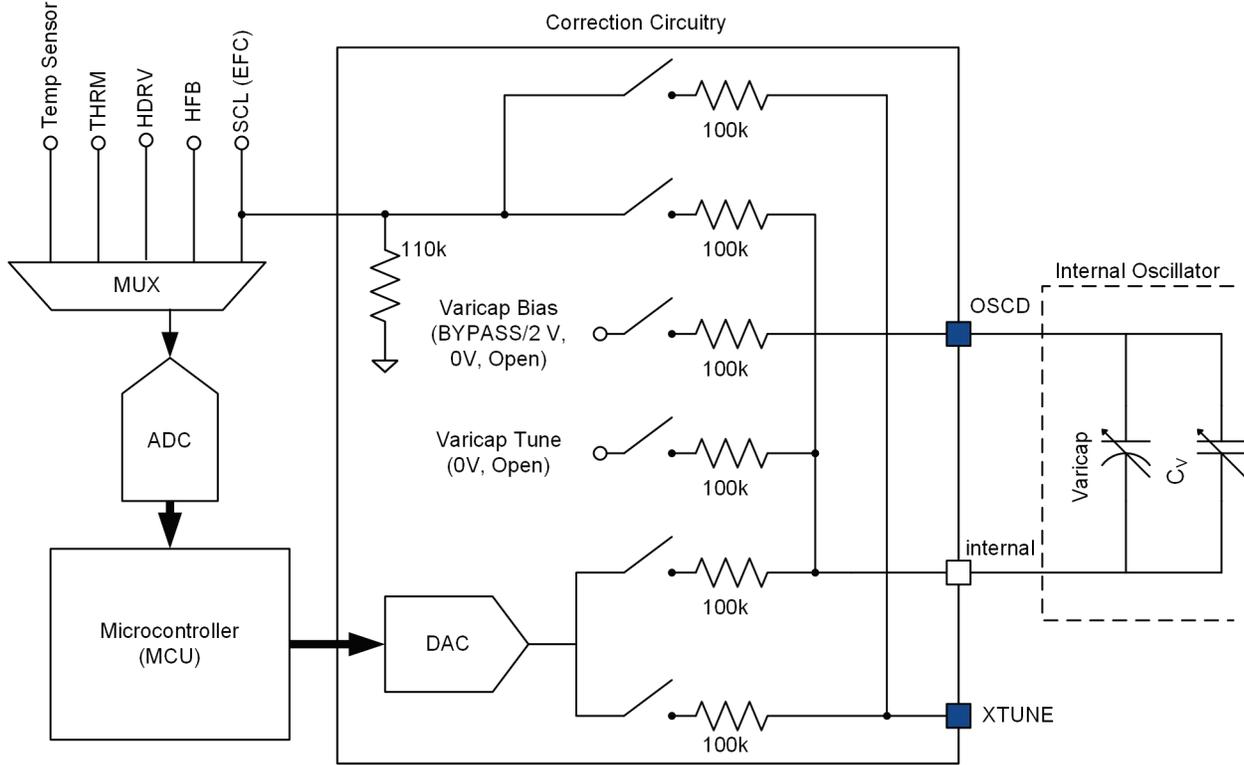


Figure 13 Correction System Diagram

Internal Temperature Sensor

The internal temperature sensor is sampled and digitized by the ADC to provide a 12-bit resolution temperature measurement of the IC. *The measured value is the temperature of the IC substrate.* This value is an indicator of the oscillator crystal temperature with proper module construction. Alternatively, an external thermistor (through the THRM pin) can be used for temperature measurements, correction, and monitoring. The internal temperature sensor is located near the center of the die and is calibrated during production test. Reference Design Examples and Application Notes for more information about thermal coupling.

Analog to Digital Converter & MUX

The ADC is a Successive Approximation architecture (SAR) in combination with a multi-channel input MUX. This architecture provides medium conversion speed and digitizes certain internal signals required to implement the correction algorithm. Control of the ADC and MUX is self-contained within the TM200 software. The THRM pin is available for additional external temperature measurements. Please reference the Application Notes for more information about using the THRM and MUX inputs.

Power Domains

The TM200 operates with the following external voltage domains:

- VDDA - 3.3V Main analog supply
 - Required supply voltage
- VDDH1 & VDDH2 – 3.3V Internal Heaters Supplies
 - Required for internal heater usage
- BYPASS – Internal Oscillator Supply (connection options listed below)
 - Shorted to VDDA
 - Internal 2.9V Regulator
 - External regulator

Upon application of VDDA power, the POR (Power on Reset)/Power Sequencing block enables the bandgap and 1.8V regulator. Other internal regulators startup with the proper delays defined within the IC. The timing control and power sequencing ensures the MCU, memory, and analog blocks start up in the correct sequence. The POR structure and startup sequencing makes the IC tolerant to wide variations in supply rise time up to 1sec. If the internal 2.9V BYPASS regulator is enabled, a 1nF capacitor on the BYPASS pin to ground is required for stability.

The BYPASS pin (oscillator supply) has 3 connection options. The first is to short it to VDDA. Alternately, the oscillator supply can be decoupled from VDDA and driven with the Internal 2.9V Regulator. Lastly, the BYPASS pin can be driven by a separate external regulator. Further information is available in the Application Notes.

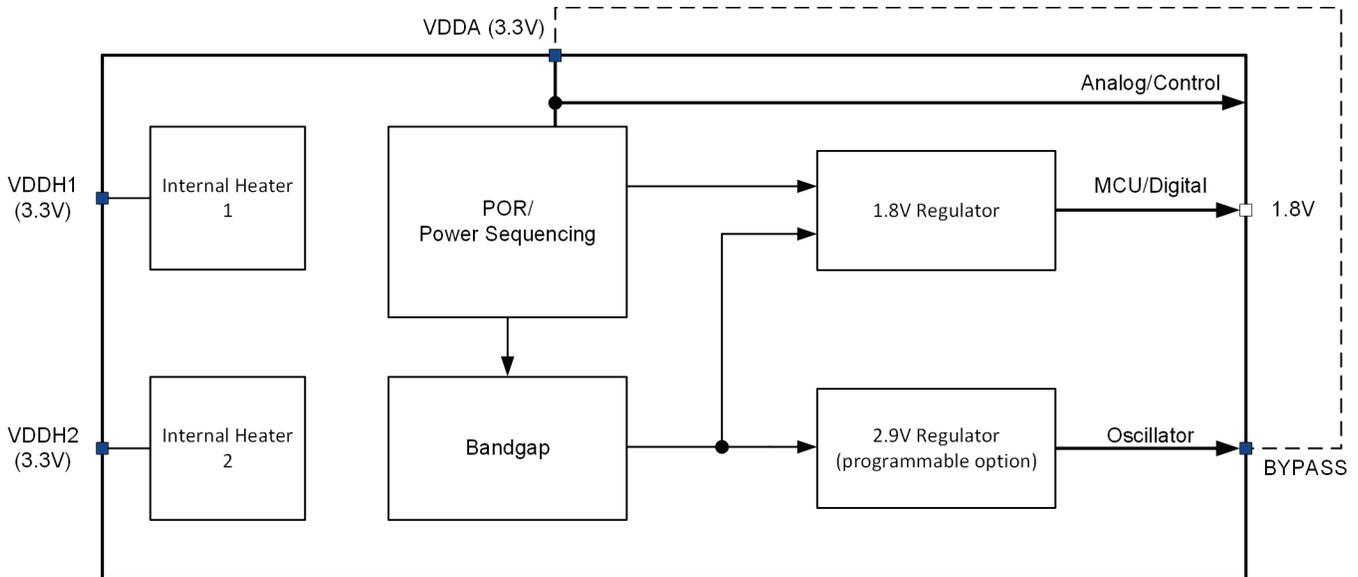


Figure 14 Supply and Voltage Domains

Microcontroller & Memory

The control unit for the IC is an embedded 8-bit microcontroller (MCU) including ROM, RAM, and OTP programmable memory. The microcontroller’s main purpose is to configure, store, and adjust parameters. The embedded firmware actively tunes the crystal based on the sensed temperature.

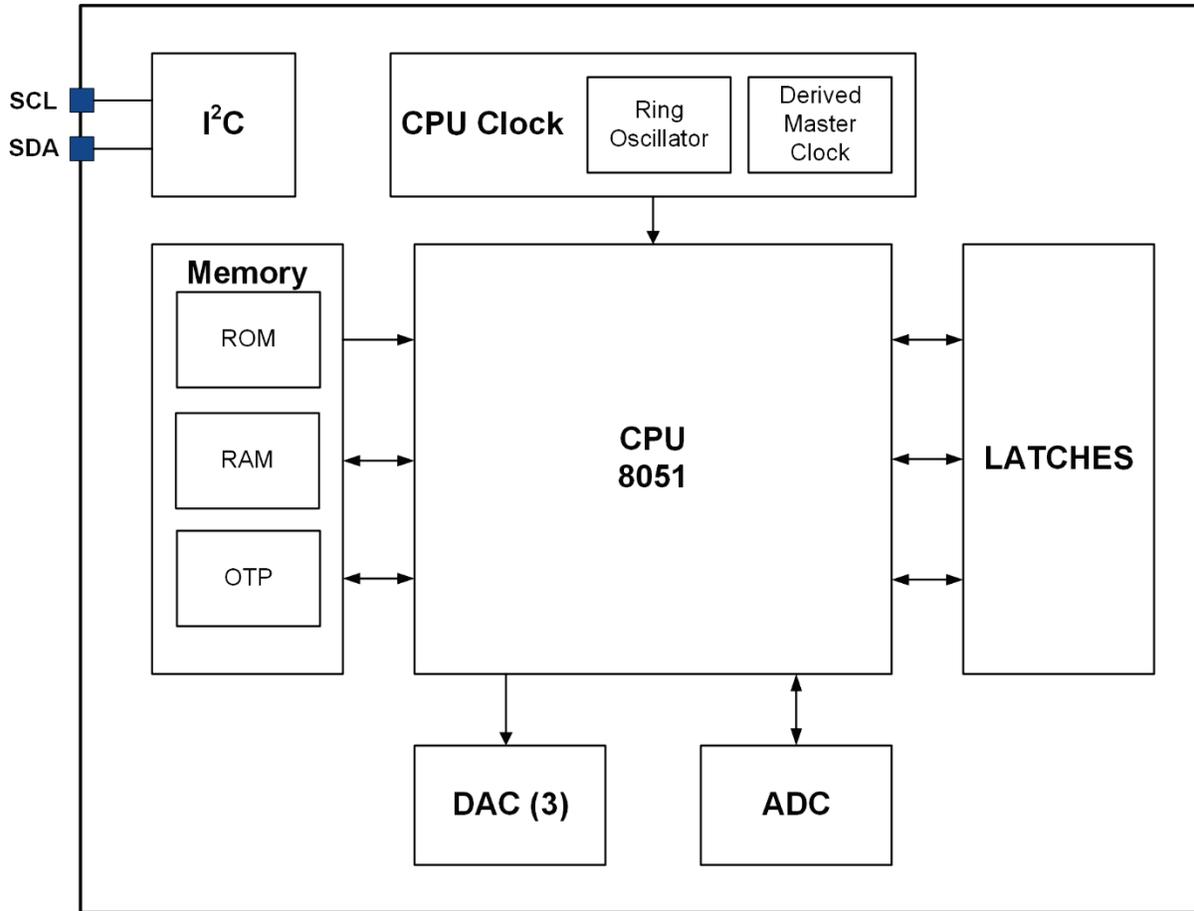


Figure 15 Digital Architecture

1. I²C Communications

Setup of the TM200 is supported via the I²C interface. Refer to the *TMx00 Programming Reference Manual* for details of the commands.

Table 11 TM200 Communication Interface

TM200 Communication Interface	
Interface Type	I²C Slave 3.3V open drain external pullups required < 10kΩ when active
Max Data Rate	100kbps
Address	5A hex
Data Pin	SDA
Clock Pin	SCL

2. Programmable Memory

The nonvolatile programmable memory (OTP) allows customers to store TM200 setup items including oscillator setup, OCXO frequency corrections over temperature, production serial numbers/trackability information, and other items as needed.

Typically, test sequences and program code will be programmed into the OTP memory during Hexius' production test. For customer production flows, the specific customer parameters for operational modes and oscillator configuration are initially loaded into RAM during the testing and burn-in phase. When those parameters are determined to be stable, commands issued to the microcontroller via the I²C interface write the resulting setup parameters into the nonvolatile OTP memory. Each time power is applied to the TM200, the contents of the nonvolatile OTP memory are used to configure the IC to the desired state.

Each OTP memory location can only be written one time. However, the OTP memory contains several subsections which allow effectively multiple rewrites (6) of the setup parameters, allowing rework and fine adjustment after burn-in and aging test cycles.

The OTP memory has a read temperature range of -40C to +125C, with a programming temperature range of 0C to 50C. For best programming results when writing OTP code sets, the VDDA supply voltage should be set to the maximum value, 3.465V.

Microcontroller Clock Source

No external clock source is required for the microcontroller. At power on reset, an internal self-starting clock of nominally 10MHz (ring oscillator) provides the master clock to the microcontroller. Under software control, the microcontroller clock source can be switched glitch-free from the ring oscillator to a signal from the crystal oscillator. Operating the microcontroller from the crystal oscillator will likely result in lower noise spurs from a common clock source. The microcontroller target clock speed is between 1 and 10 MHz, and internal frequency dividers provide the proper clock rate for OCXO outputs exceeding 10MHz.

A detector circuit determines if a stable oscillator operation is available. The processor reads a flag from the detector circuit and controls the switch to the main oscillator as commanded by software. If the main oscillator fails, the μP will automatically switch back over to the internal ring oscillator.

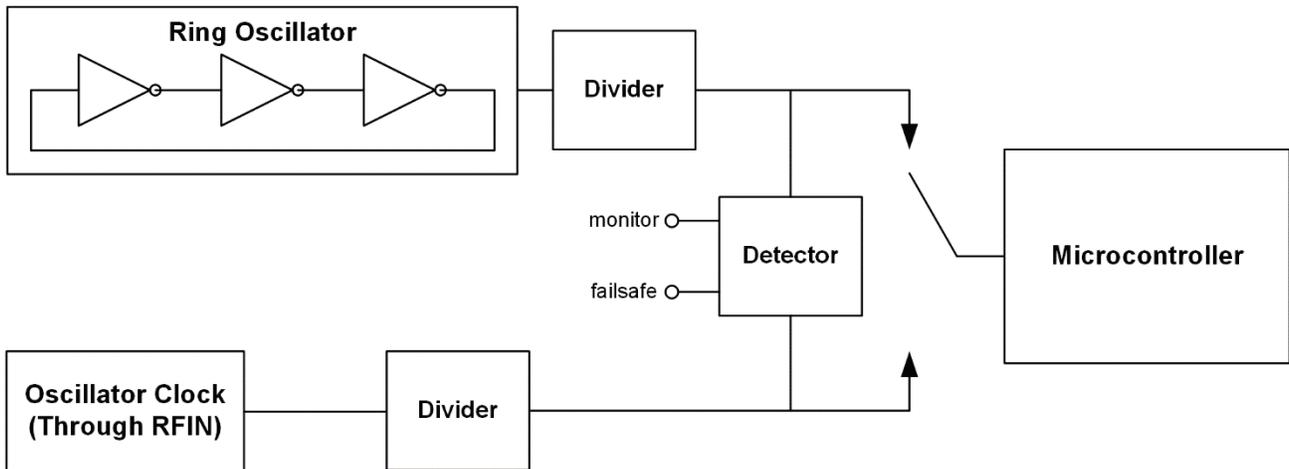


Figure 16 Clock Source Switching

OCXO TEMPERATURE CORRECTION ALGORITHM OVERVIEW

The TM200 supports three correction algorithms to compensate for temperature and voltage non-idealities:

1. **Lookup Table** – Temperature correction algorithm
2. **Temperature Polynomial Curve Fit** – Temperature correction algorithm
3. **Supply Voltage Curve Fit** – Voltage correction algorithm

The TM200 correction algorithms use integer numbers (digital codes) that represent temperatures and voltages to make compensation adjustments. The ADC converts analog signals into the digital domain for the MCU to calculate the appropriate Correction DAC input code and produce an analog correction voltage.

The first two algorithms use a *Temp Code* input to generate a *CorrDAC Code* from the Correction DAC output to correct frequency variations over temperature. Only one of the temperature correction algorithms may be used during operation.

The *Temp Code* value is an integer with the range of 0 to 4095 and corresponds to the temperature being measured and digitized through the ADC. A -40C to 90C temperature range will utilize a *Temp Code* range of approximately 2000 to 3200. The *Temp Code* is produced from either the IC internal temperature sensor or an external thermistor (via the THRM pin).

The *CorrDAC Code* value is an integer with the range of 0 to 4095 and corresponds to the DAC input code needed to vary the capacitance across an external varactor or the internal TM200 Varicap to correct the frequency variation for a given temperature.

The *CorrDAC Voltage* is resulting Correction DAC output voltage for a given *CorrDAC Code*. It is calculated by multiplying the Correction DAC’s reference voltage by the ratio of the *CorrDAC Code* to the Correction DAC’s full-scale code (4095).

$$\text{CorrDAC Voltage} = \frac{\text{CorrDAC Code}}{4095} * \text{BYPASS Pin Voltage}$$

As a brief relationship example, a measured temperature of 25C may produce a *Temp Code* of 2541 and results in a *CorrDAC Code* of 1983 and a *CorrDAC Voltage* of 1.4043V for the correct center frequency of a unique OCXO assembly.

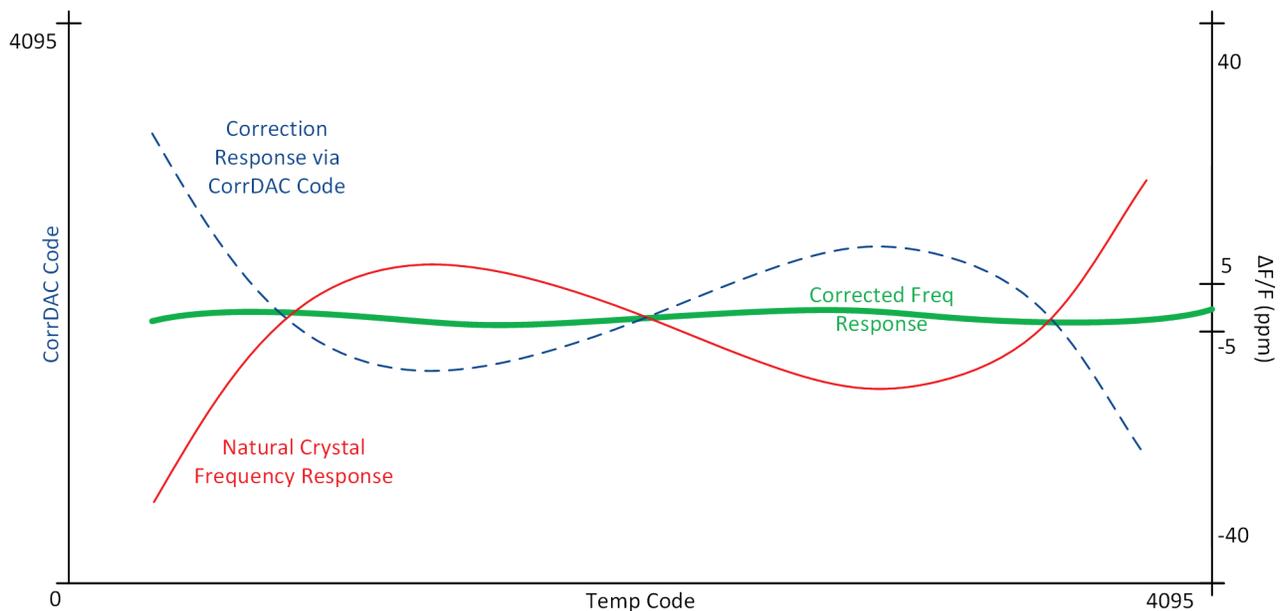


Figure 17 Temp Code and CorrDac Code Relationship

Adjustable Timing Parameters

The TM200 correction mechanism is a hybrid analog/digital implementation and has several adjustable timing parameters that allow customers to tune timing modules to the time constants of the intended applications. The adjustments also implement low pass filters to reduce crystal adjustment transients.

Supported adjustable timing parameters include:

Temperature Sample Interval – This sets the time interval (in ms) for measuring the temperature sensor and VDDA value. The interval is between 20ms and 2550ms. Both the temperature and VDDA readings are averaged over 8 sample intervals, updated at each sample interval (rolling average).

Frequency Correction Interval - This sets the time interval (in ms) for updating the Correction DAC value applied to the Varicap or external varactor. The interval is between 20ms and 2550ms.

Averaging Intervals - This sets the number of Frequency Correction Intervals used to calculate an average DAC correction value, updated each correction interval (rolling average). The averaging is between 1 and 16.

Lookup Table Curve Fit

The Lookup Table correction technique uses the measured reading from the IC temperature sensor or external thermistor (*Temp Code*) and generates a *CorrDAC Code* via a lookup table.

The lookup table is arranged from the lowest *Temp Code* to the highest *Temp Code* with up to 80 defined points. The spacing between the points is user defined to account for changing crystal temperature coefficient slopes. The appropriate DAC correction code (*CorrDac Code*) between the defined *Temp Code* points is calculated by linear interpolation.

Temp	Temp Code	CorrDAC Code
-40	2005	2720
-30	2085	2318
-20	2167	2028
-10	2250	1856
0	2333	1794
10	2416	1822
20	2500	1906
25	2542	1961
30	2584	2014
40	2669	2124
50	2754	2164
60	2841	2142
70	2923	2015
80	3009	1723
90	3096	1032

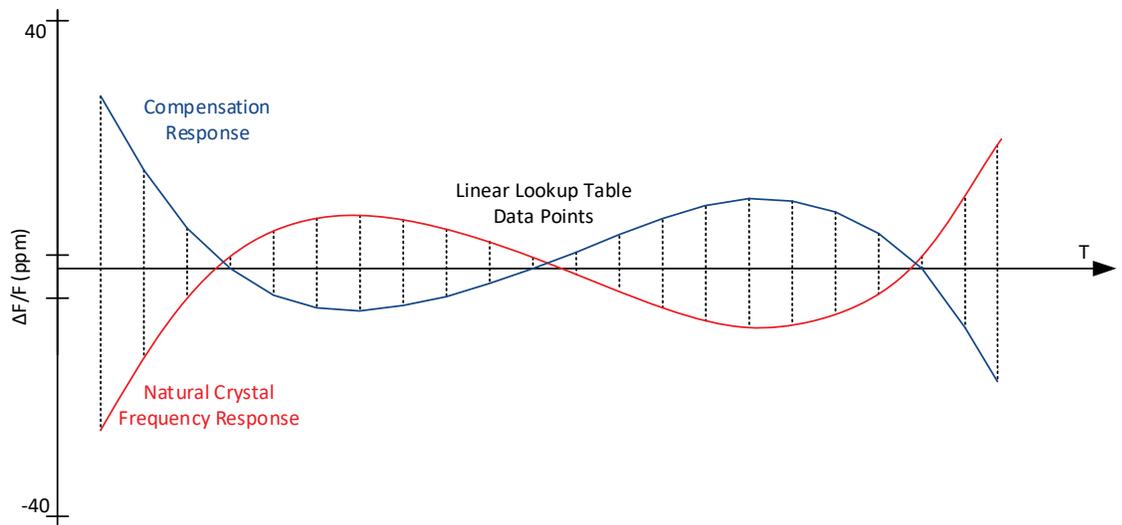


Figure 18 Linear Lookup Table Concept

Temperature Correction Polynomial Curve Fit

The temperature polynomial curve fit correction technique uses the measured temperature reading from the IC sensor or external thermistor (*Temp Code*) and calculates a *CorrDAC Voltage* via polynomial curve fit using the correction order coefficients, $a_0 - a_9$.

The correction process computes the Correction DAC voltage needed for best correction. The *CorrDAC Voltage* range is from 0V up the voltage of the BYPASS pin (typically, 2.9V or 3.3V depending on configuration). The correction value is converted into a 12-bit DAC input digital code (*CorrDAC Code*), 0 for 0V, and 4095 for the max BYPASS Voltage. The internal tuning Varicap operates over a range of 0V to 2.9V, so the *CorrDAC Voltage* needs to be limited when BYPASS is operated from a supply greater than 2.9V.

$$Corr_{temp}(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 + a_7x^7 + a_8x^8 + a_9x^9$$

$x = TempCodeNormalized$: *TempCode normalized for Mean and Standard Deviation*

$$Corr_{temp}(x) = CorrDAC Voltage = Correction DAC voltage$$

To use the polynomial curve fit algorithm, the following data needs to be selected or entered:

1. Desired correction order: For some applications 3rd or 5th order corrections may produce better results over temperature than a 7th or 9th order correction. This item can be set as needed for each oscillator application.
2. *Temp Code* Mean and *Temp Code* Std Dev: Measure the module over temperature and capture the *Temp Code* for each measured temperature point. Compute the mean and standard deviation of the *Temp Code* values. Then scale the *Temp Code* values by the mean and standard deviation generating x (*Temp Code Normalized*) for the above equation.
3. *CorrDAC Codes over Temperature*: As part of the module measurements over temperature, determine the *CorrDAC Code* that produces the least error. Convert the *CorrDAC Code* to *CorrDAC Voltage* by scaling it, 0 to 4095 for the voltage range 0 to the BYPASS pin Voltage. *CorrDAC Voltage* is $Corr_{temp}(x)$ in the equation above.
4. Use polynomial curve fit software to find the values of a_0 to a_n based on x and $Corr_{temp}(x)$.
5. Enter the coefficients, $a_0 - a_9$, the *Temp Code* mean, and the *Temp Code* Std Dev for the respective correction order. The coefficients are single precision floating point numbers stored in the microcontroller. Single precision floating point numbers have 7-8 decimal digits of precision and ensure that all significant digits are entered into the microcontroller.

Please refer to the separate application document titled *TMx00 Correction Algorithm Development* for details.

Supply Voltage Curve Fit

The *CorrDAC Voltage* values are not overly sensitive to supply voltage (VDDA) variation when the internal BYPASS regulator is enabled. The *Temp Code Normalized* values have some dependency on supply voltage. This means that supply voltage variations will shift the *Temp Code* values. The supply voltage polynomial curve fit correction techniques are optional enhanced correction methods that generate adjustment terms to account for this shift.

A *Corr_{voltage}* term corrects for frequency shifts over supply voltage variation and uses the coefficients, $b_1 - b_3$.

A *Corr_{voltage_temp}* term corrects for frequency shifts from cross correlated supply voltage and temperature variation and uses the coefficients, $c_1 - c_3$.

The user selects whether these correction terms are applied to either the *Temp Code* or *CorrDAC Code* depending on the architecture and sensitivity of supply voltage movement of the OCXO module. Each choice has further options regarding the order of correction desired.

Temp Code Adjustment Option

Because the supply voltage range of the TM200 is $\pm 5\%$, the standard deviation of the *VDDA Code* range is set internally with respect to the nominal *VDDA Code*.

$$VDDA_{SD} = \text{Standard deviation of VDDA}$$

The Standard Deviation is defined so a 5% high supply voltage gives a $VDDA_{SD}$ (or σ) of +3.0, and a 5% low supply gives a $VDDA_{SD}$ of -3.0.

$$VDDA_{SD} = VDDACode_{NOM} \left(\frac{0.05}{3} \right)$$

$VDDACode_{NOM}$ is the ADC code value measured by the IC when the VDDA supply voltage is 3.3V. A typical ADC code value is 2330. Note that the VDDA ADC input is divided by 2, so the 2330 code represents an input value of 1.65V.

$$\Delta VDDA = \frac{VDDACode_{Meas} - VDDACode_{Nom}}{VDDA_{SD}}$$

Applying the correction by adjusting the *TempCode*:

$$Temp_{ADJ} = TempCodeNormalized + \Delta TempCode(\Delta VDDA)$$

Where:

$Temp_{ADJ}$ is the new *TempCodeNormalized* value input into the main *Corr_{temp}(x)* function for frequency correction

$\Delta TempCode$ is the *Temp Code* adjustment based on voltage and temperature measurements

Temp Code Corr_{voltage} 1st Order Correction Option

$$\Delta TempCode(\Delta VDDA) = Corr_{voltage}(\Delta VDDA) = b_1(\Delta VDDA)$$

Temp Code Corr_{voltage} 3rd Order Correction Option

$$\Delta TempCode(\Delta VDDA) = Corr_{voltage}(\Delta VDDA) = b_1(\Delta VDDA) + b_2(\Delta VDDA)^2 + b_3(\Delta VDDA)^3$$

Temp Code Corr_{voltage} & Corr_{voltage_temp} 3rd Order Correction Option

$$\begin{aligned} \Delta TempCode(\Delta VDDA) &= Corr_{voltage}(\Delta VDDA) + Corr_{voltage_temp}(\Delta VDDA) \\ &= b_1(\Delta VDDA) + b_2(\Delta VDDA)^2 + b_3(\Delta VDDA)^3 + c_1(\Delta VDDA)(TempCode) \\ &\quad + c_2(\Delta VDDA)^2(TempCode) + c_3(\Delta VDDA)(TempCode)^2 \end{aligned}$$

CorrDAC Code Adjustment Option

Applying the correction by adjusting the *CorrDAC Code*:

$$CorrDAC_{ADJ} = CorrDAC\ Code + \Delta CorrDAC\ Code(\Delta VDDA) - \text{when using the Lookup Table Correction}$$

Or

$$CorrDAC_{ADJ} = CorrDAC\ Voltage + \Delta CorrDAC\ Voltage(\Delta VDDA) - \text{when using the Polynomial Correction}$$

Where:

$CorrDAC_{ADJ}$ is the new *CorrDAC Code* value output for frequency correction (Lookup Table Correction)

$\Delta CorrDAC\ Voltage$ is the new *CorrDAC Voltage* output for frequency correction (Polynomial Correction)

$\Delta CorrDAC\ Code$ is the *CorrDAC Code/Voltage* adjustment based on voltage and temperature measurements.

CorrDAC Code $Corr_{voltage}$ 1st Order Correction Option

$$\Delta CorrDAC\ Code(\Delta VDDA) = Corr_{voltage}(\Delta VDDA) = b_1(\Delta VDDA)$$

CorrDAC Code $Corr_{voltage}$ 3rd Order Correction Option

$$\Delta CorrDAC\ Code(\Delta VDDA) = Corr_{voltage}(\Delta VDDA) = b_1(\Delta VDDA) + b_2(\Delta VDDA)^2 + b_3(\Delta VDDA)^3$$

CorrDAC Code $Corr_{voltage}$ & $Corr_{voltage_temp}$ 3rd Order Correction Option

$$\Delta CorrDAC\ Code(\Delta VDDA) = Corr_{voltage}(\Delta VDDA) + Corr_{voltage_temp}(\Delta VDDA) = b_1(\Delta VDDA) + b_2(\Delta VDDA)^2 + b_3(\Delta VDDA)^3 + c_1(\Delta VDDA)(TempCode) + c_2(\Delta VDDA)^2(TempCode) + c_3(\Delta VDDA)(TempCode)^2$$

Correction Algorithm Implementation

Various methodologies exist for obtaining the unique crystal and OCXO module frequency responses across temperature during the manufacturing process. Please refer to the separate application document titled *TMx00 Correction Algorithm Development* for details regarding the development flow of each correction algorithm and additional information.

For more information regarding the memory structure and commands needed to program the TM200, please refer to the *TMx00 Programming Reference Manual* or use the TM200 Control Program software to enter the values.

APPLICATION NOTES

Oscillator Power Supply Options

The BYPASS pin/net is the internal Pierce oscillator’s power supply with 3 connection options. The BYPASS pin/net should be operated between 2.9V and 3.3V. (Other connections omitted. Refer to Design Examples.)

BYPASS Shorted to VDDA

Connecting the BYPASS pin directly to the VDDA pin operates the oscillator supply voltage at 3.3V. If the incoming VDDA supply is a well-regulated low noise source, this can produce excellent oscillator phase noise performance. 22uF and 0.01uF external bypass capacitors are highly recommended located in very close proximity to the resulting supply node to reduce or eliminate spurious energy.

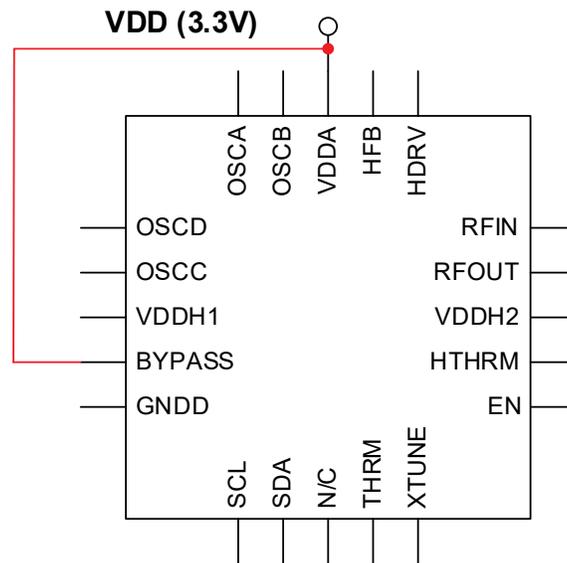


Figure 19 Oscillator Power Supply (BYPASS) Connected to VDDA

Internal BYPASS Regulator

Enabling the TM200’s Internal 2.9V Regulator provides a low noise supply for the oscillator and decouples it from the VDDA supply without the need for a separate regulator. The BYPASS pin needs to have 1nF capacitor externally to stabilize the regulator. The noise of the internal regulator is very low given the size constraints of the IC.

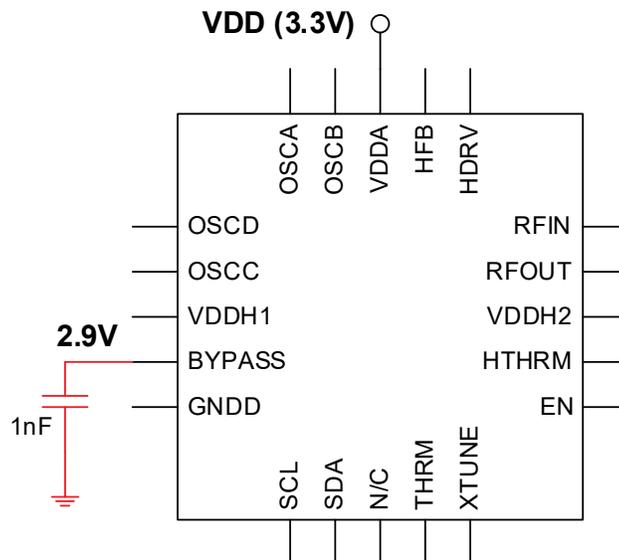


Figure 20 Oscillator Power Supply (BYPASS) Powered by Internal Regulator

External BYPASS Regulator

Connecting the BYPASS pin to an external regulator also decouples the oscillator from VDDA and can provide a lower noise supply for the oscillator for higher performance applications where the oscillator noise is below that of the internal regulator. Potential regulator choices include the Texas Instruments LP5907 or Analog Devices AD7151.

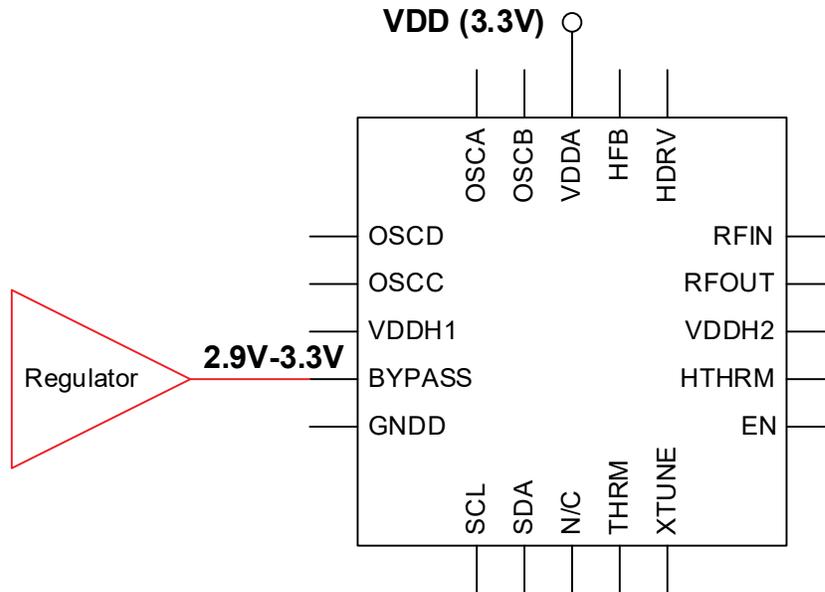


Figure 21 Oscillator Power Supply (BYPASS) Powered by External Regulator

Internal Pierce Oscillator Properties

Negative Resistance

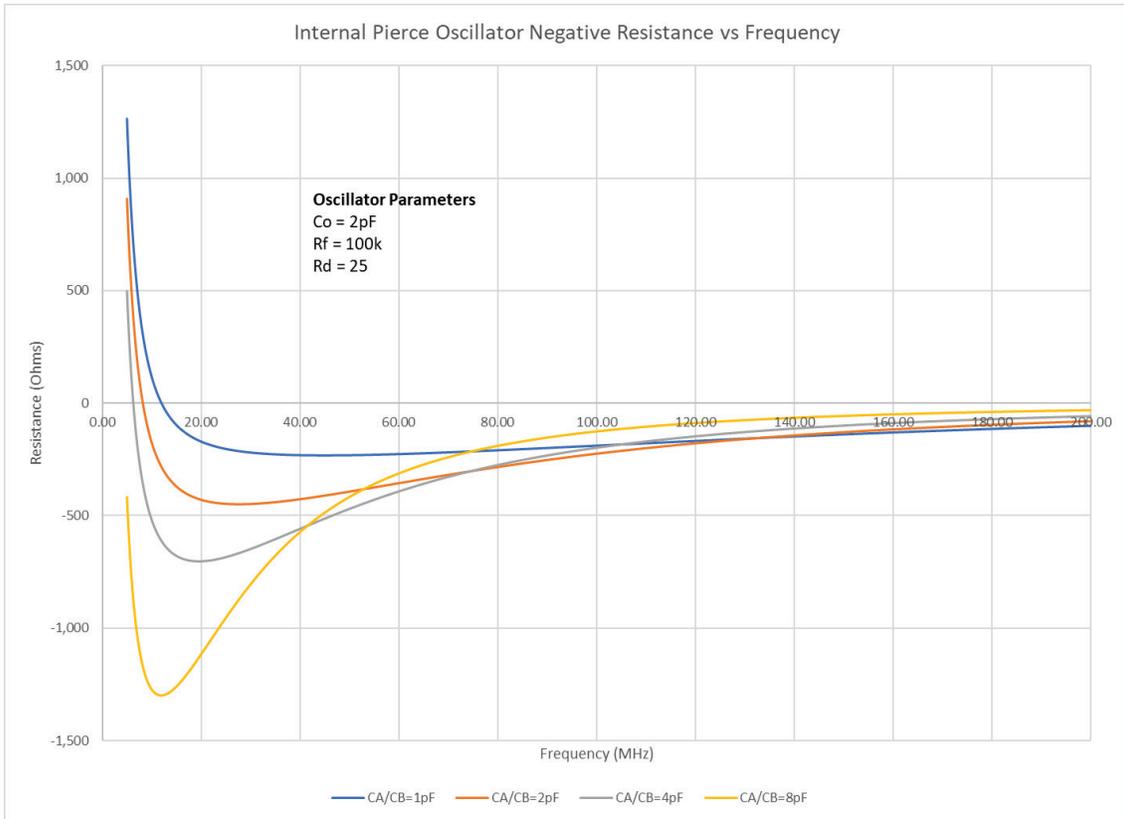


Figure 22 Pierce Oscillator Negative Resistance vs Frequency

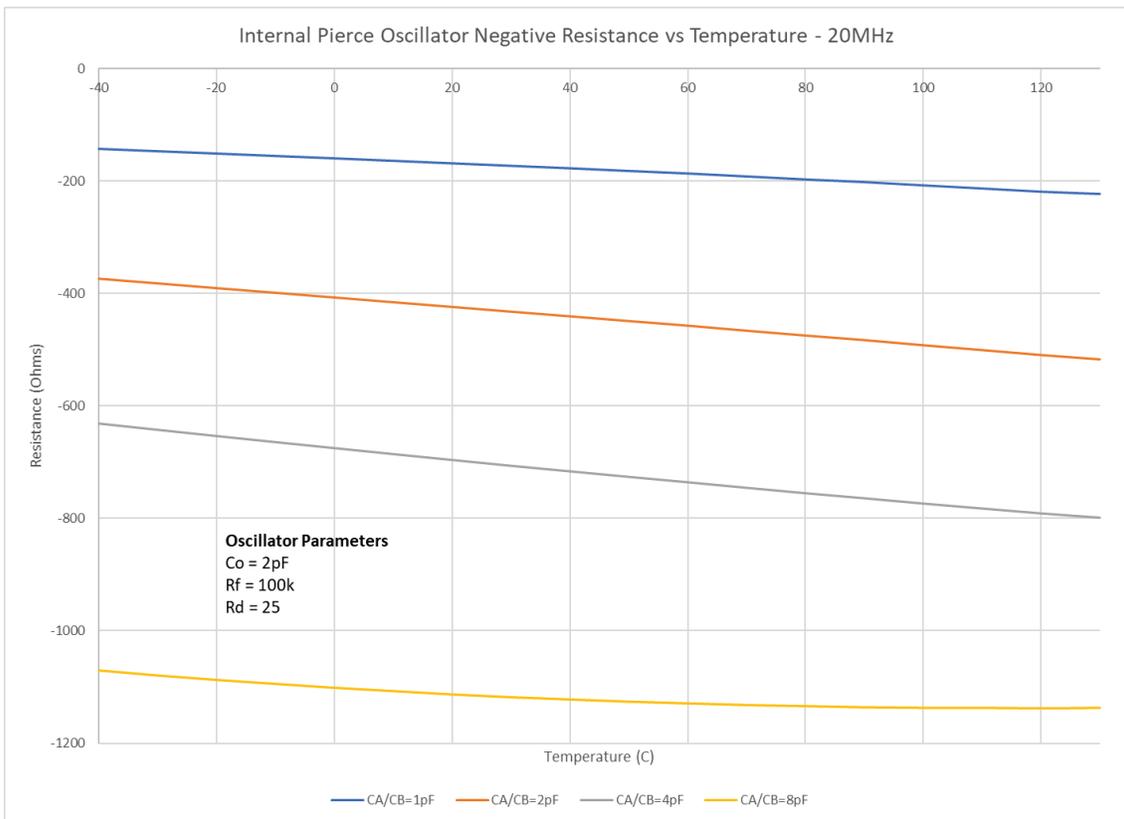


Figure 23 Pierce Oscillator Negative Resistance vs Temperature – 20MHz

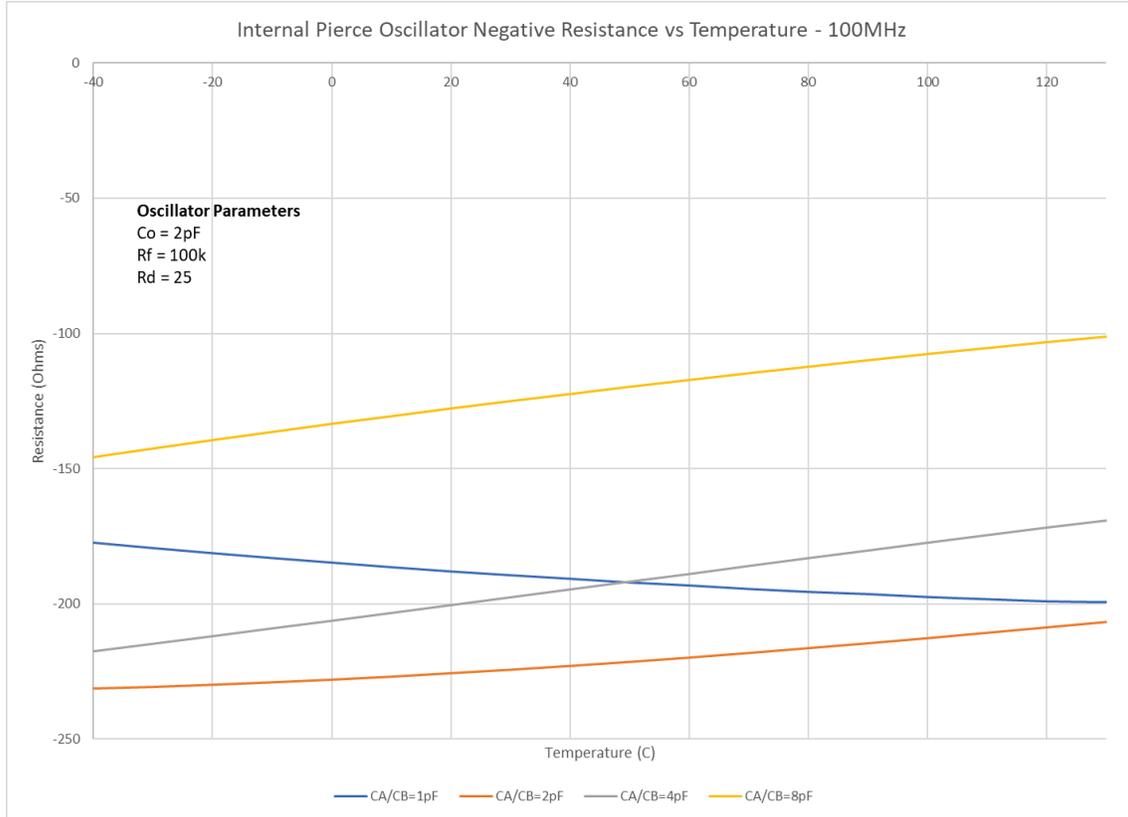


Figure 24 Pierce Oscillator Negative Resistance vs Temperature – 100MHz

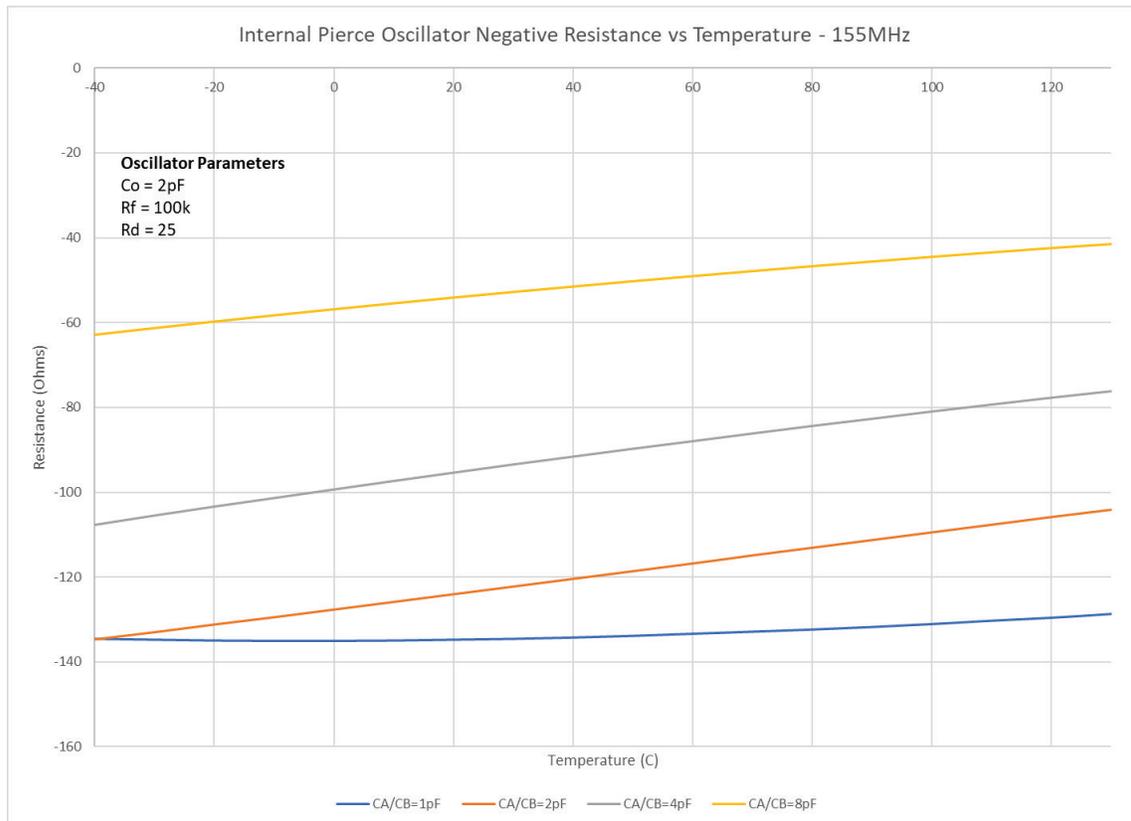


Figure 25 Pierce Oscillator Negative Resistance vs Temperature – 155MHz

Integrated Capacitors CA & CB

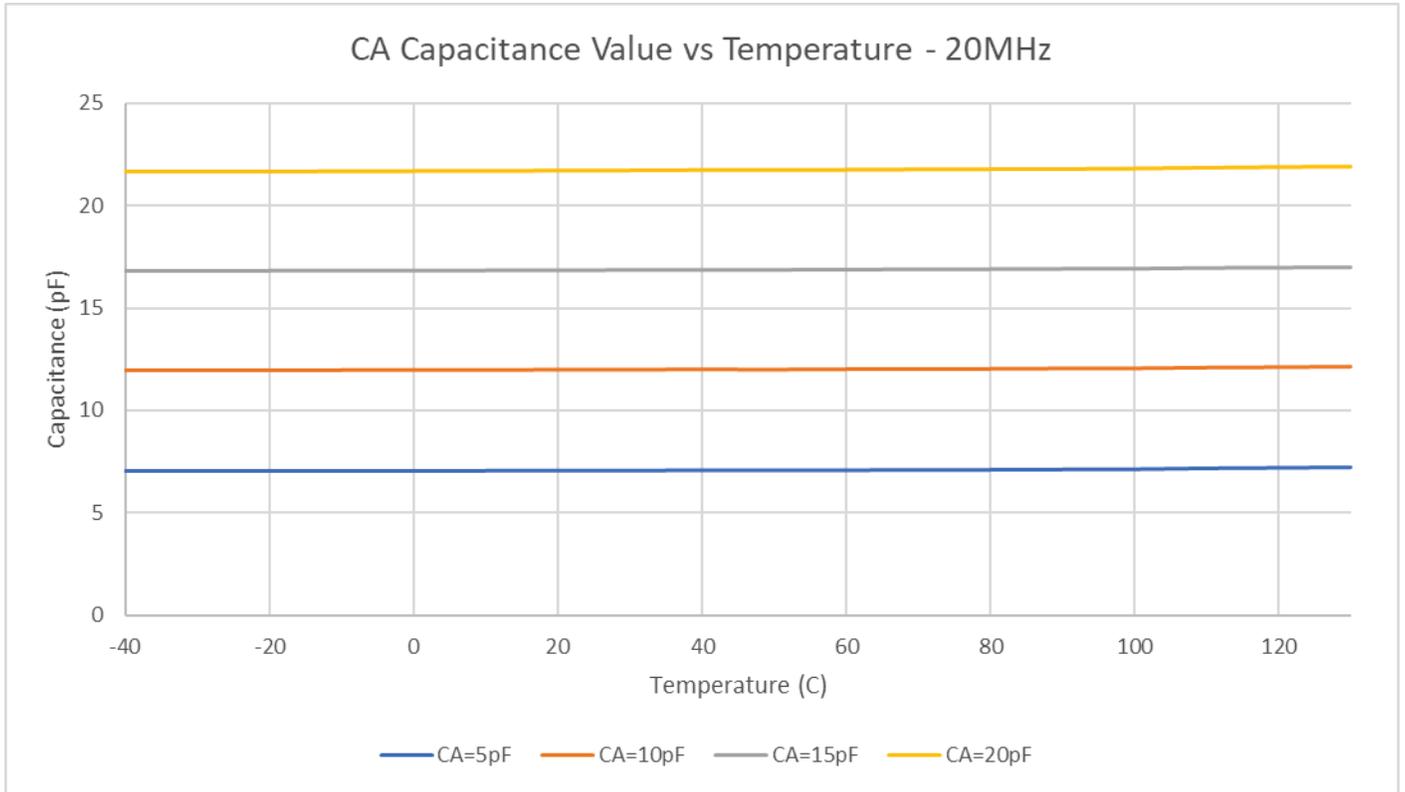


Figure 26 CA Capacitance Values vs Temperature – 20MHz

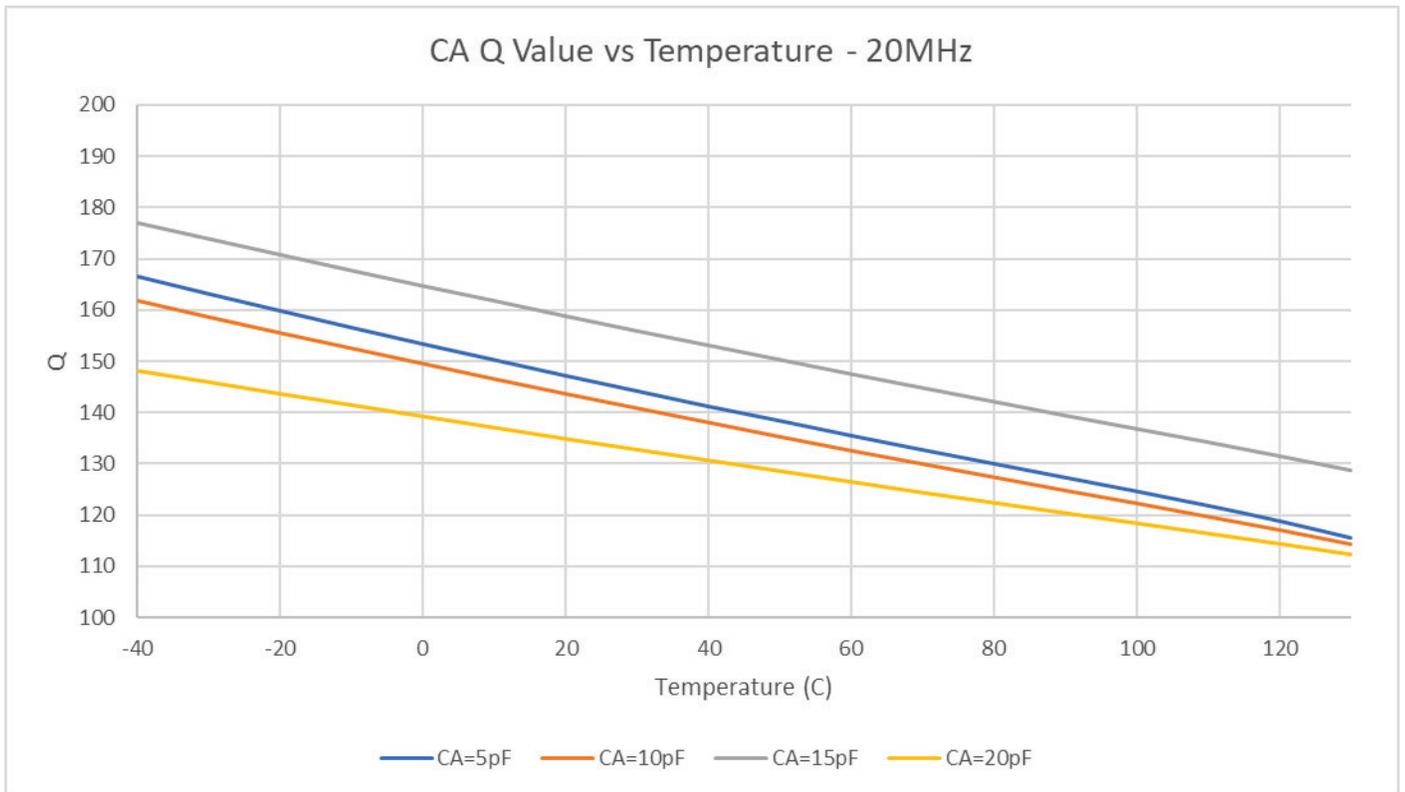


Figure 27 CA Q Values vs Temperature – 20MHz

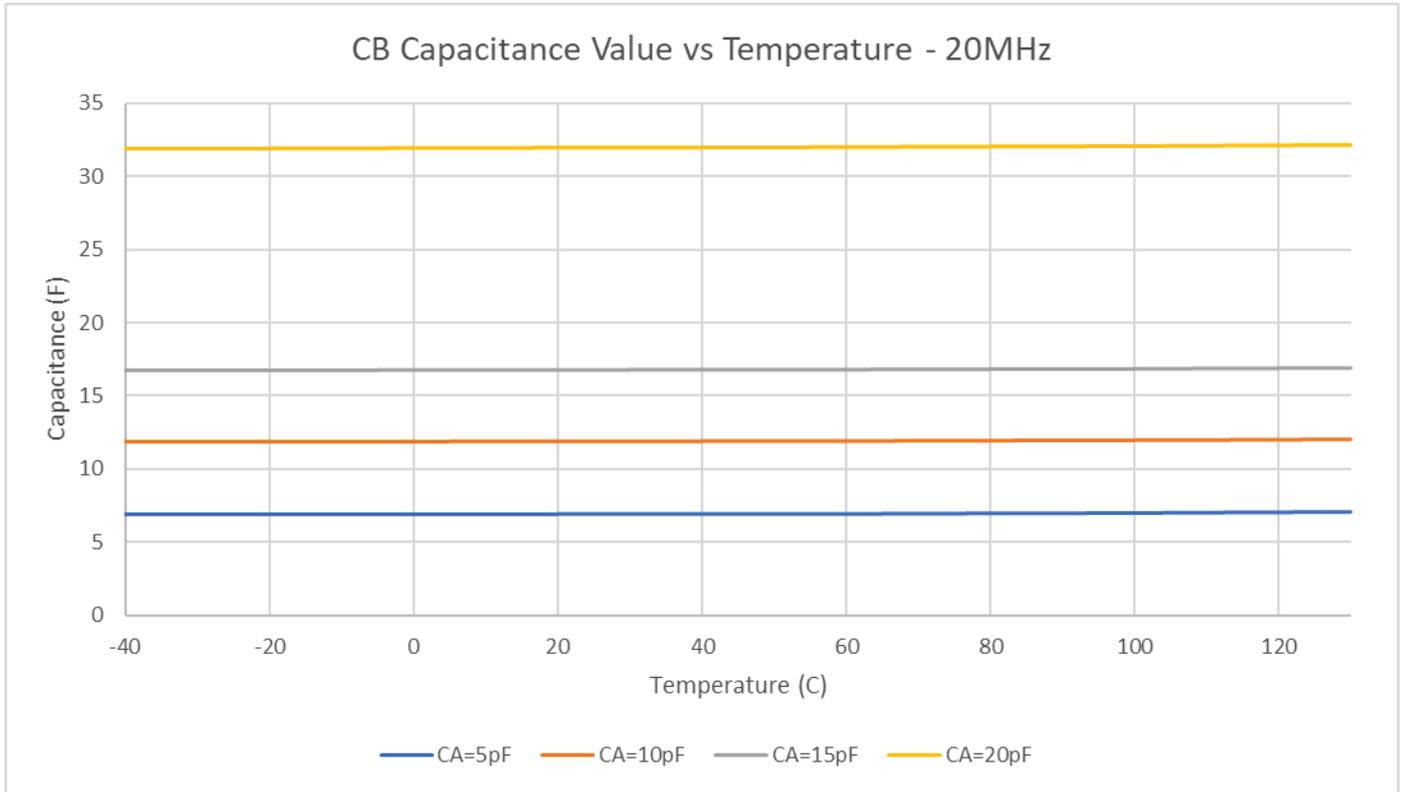


Figure 28 CB Capacitance Values vs Temperature – 20MHz

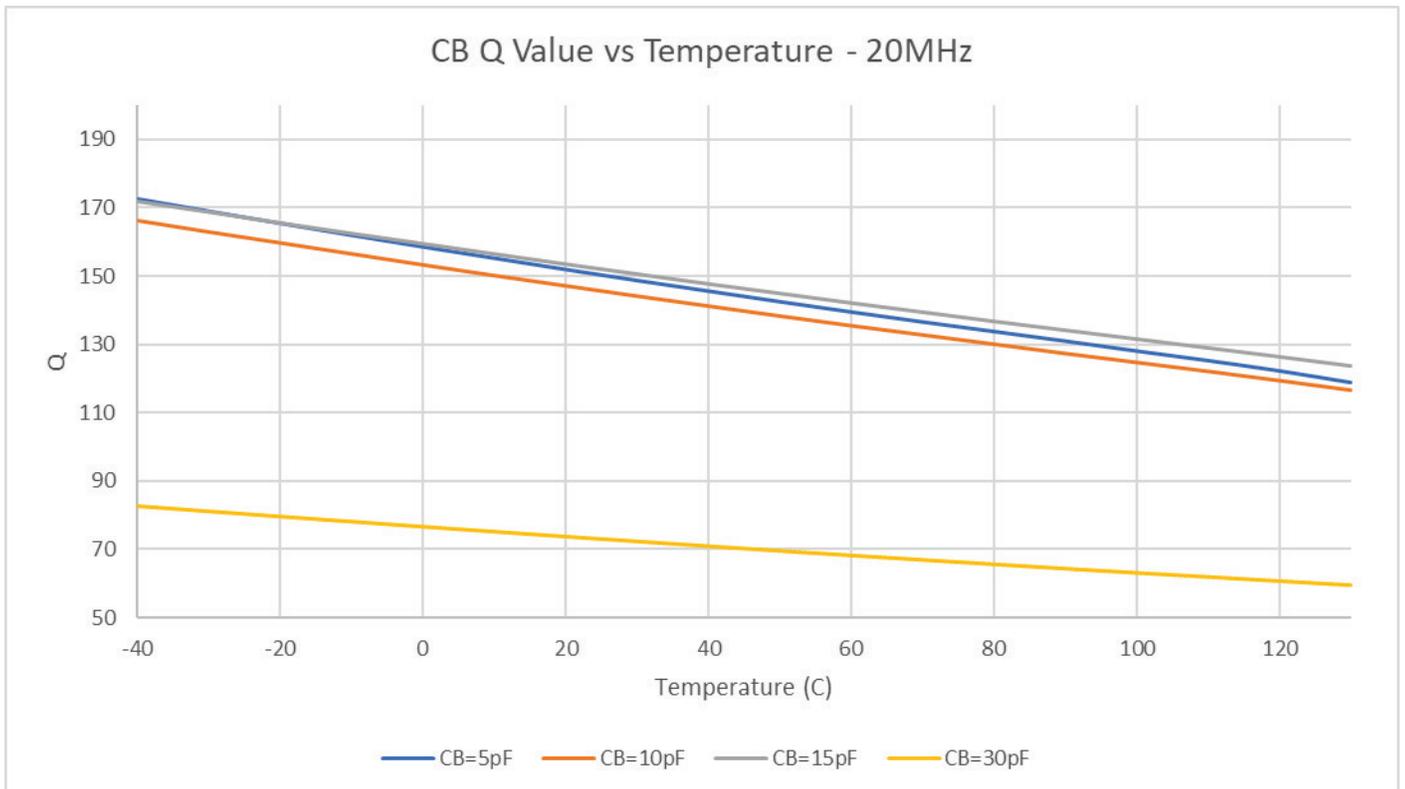


Figure 29 CB Q Values vs Temperature – 20MHz

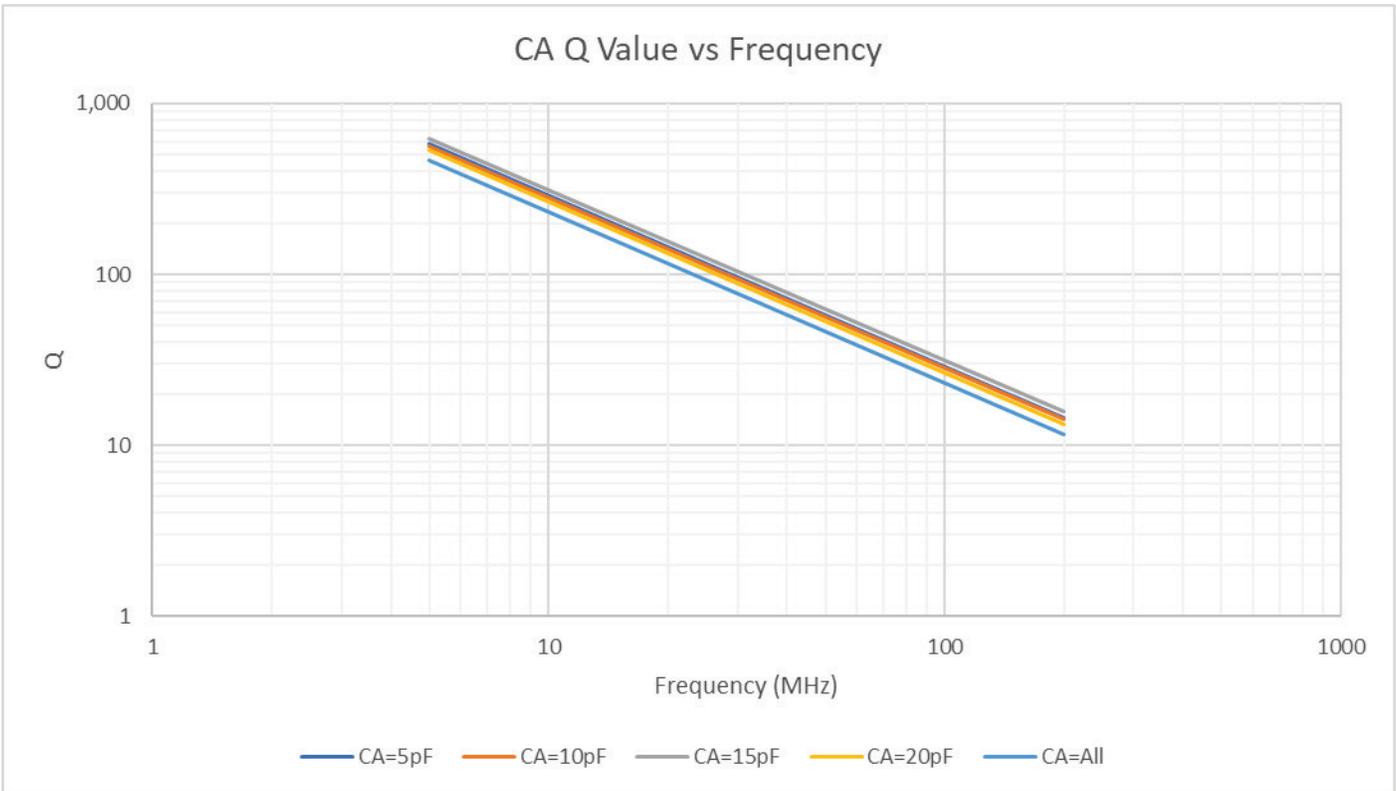


Figure 30 CA Q Values vs Frequency

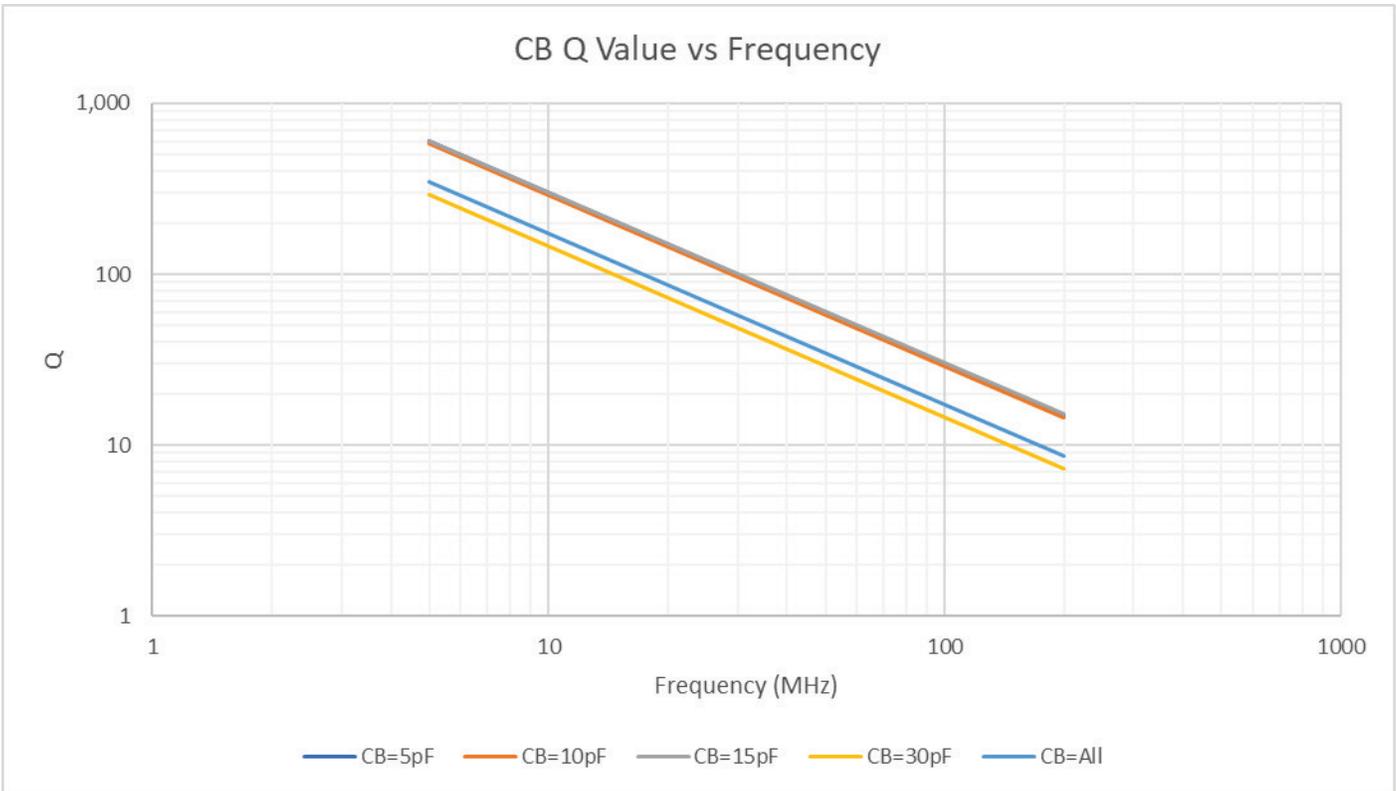


Figure 31 CB Q Values vs Frequency

Disabling Pierce Oscillator

Certain applications may require the use of an external oscillator structure. An example would be to construct a Colpitts based oscillator architecture and using the TM200 as the correction device for the oscillator. In this scenario, the internal oscillator circuit should be disabled. The proper way to disable the oscillator circuit is to do implement the following:

1. Ground the OSCA pin
2. Set C_A , C_B , C_F , C_V , and R_D to OPEN states.
3. Set R_F to 100k

Output Signal Architecture Options

The output signal can be generated with several architecture options primarily using pins RFIN and RFOUT. Other configurations are possible with careful oscillator design considerations. Output driver options include the internal TM200 RF Output Stage, an unbuffered inverter, or Hexius CF Series Fanout ICs. (Other connections omitted. Refer to Design Examples.)

RFIN TO RF Output Stage

The internal TM200 RF Output Stage restores the clock edges, makes duty cycle adjustments, and performs any necessary clock division before driving the output load. The RF Output Stage is an effective alternative to using external ICs to condition the output signal of an OCXO module. With this configuration, the MCU may be clocked with the internal ring oscillator or switched over to the crystal oscillator.

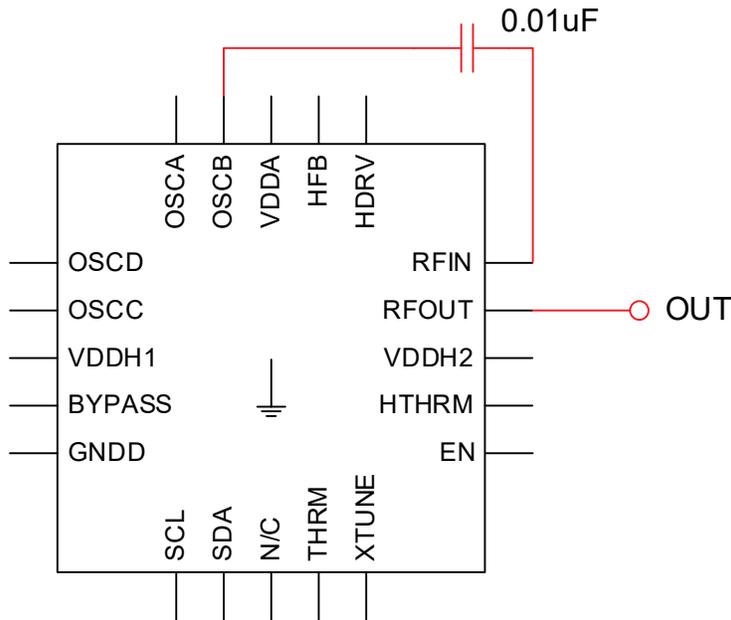


Figure 32 RFIN to RF Output Stage Option

RFIN into Inverter

If the RF Output Stage features are not needed, driving the unbuffered inverter from RFIN produces excellent phase noise floor performance while retaining the ability for duty cycle adjustment and MCU clock control. With this configuration, the MCU may be clocked with the internal ring oscillator or switched over to the crystal oscillator. The RFOUT stage needs to be disabled and the RFOUT pin should be left unconnected.

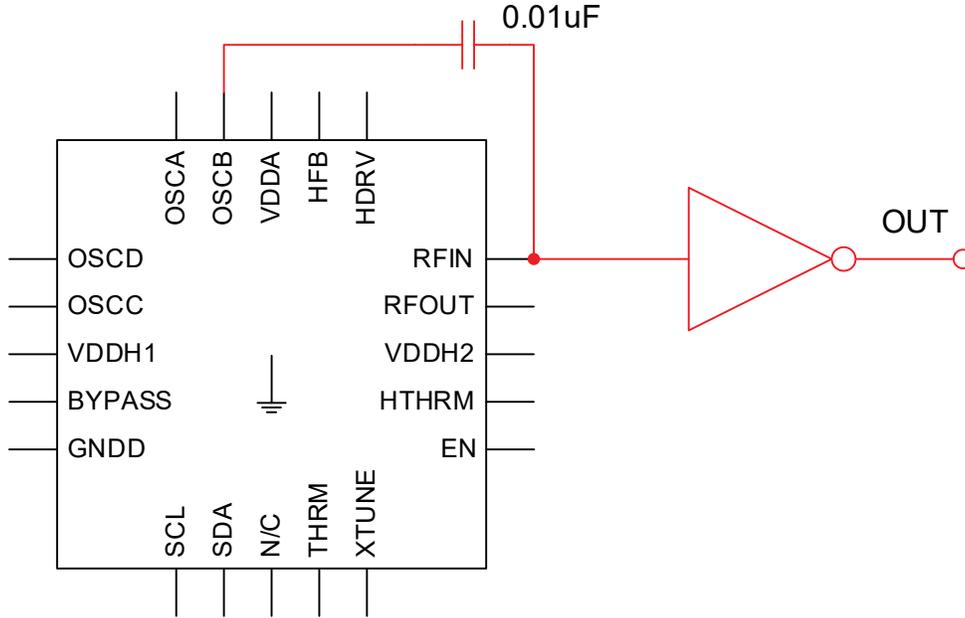


Figure 33 RFIN to Unbuffered Inverter Option

RFIN into Hexius CF Series Fanout Buffer

Another option that produces multiple output signals is to use Hexius’ CF Series of fanout buffer that produce CMOS or LVPECL outputs. The CF Series fanout buffers have frequency division and industry leading extremely low additive jitter. With this configuration, the MCU may be clocked with the internal ring oscillator or switched over to the crystal oscillator. The RFOUT stage needs to be disabled and the RFOUT pin should be left unconnected.

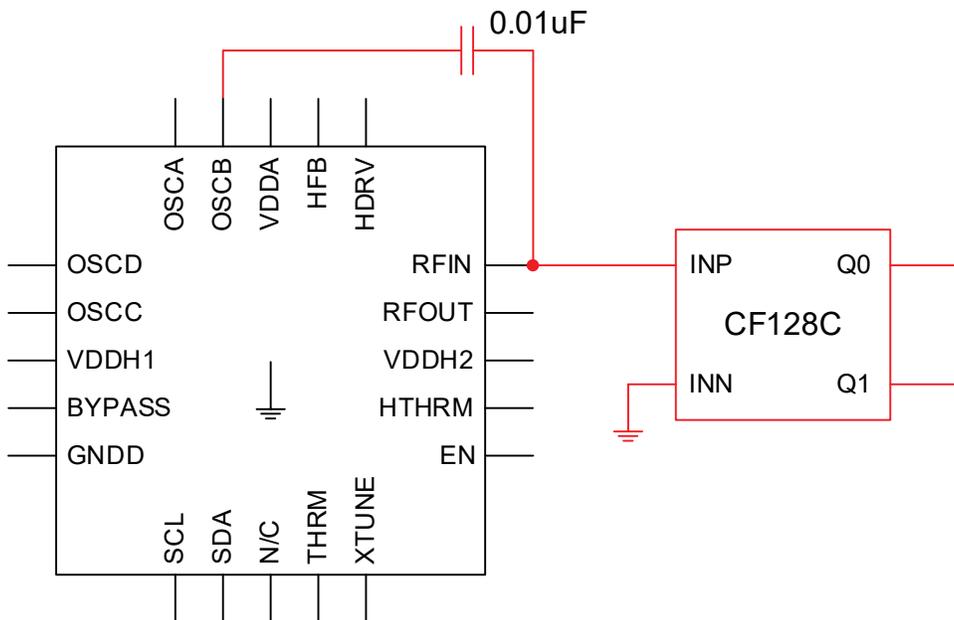


Figure 34 RFIN to Hexius CF Series Fanout Buffer

HTHRM NTC Thermistor Usage

Typical applications for HTHRM use a 100kΩ NTC (Negative Temperature Coefficient) with tight thermal coupling to the crystal. The variation of the resistance over temperature is given by the beta equation or Steinhart-Hart equation.

The beta equation is:

$$R_{T1} = R_{T0} e^{\beta \left(\frac{1}{T1} - \frac{1}{T0} \right)}$$

$T0 = \text{Reference Temperature (25C) in } ^\circ K = 298.15$

$T1 = \text{Test Temperature in } ^\circ K$

$R_{T0} = \text{Resistance at Reference Temperature} = 100k\Omega \text{ typical}$

$\beta = \text{Parameter from vendor that illustrates the value shift over temperature, typically } \sim 4200$

The beta equation is an approximation since the beta value varies somewhat over temperature. The Steinhart-Hart equation is more accurate but is not documented for all candidate thermistors.

T0 298.15
B 4200
R0 100000

Temperature	Resistance Value
-20	1223236
-10	651176
0	363024
10	210909
20	127159
30	79268
40	50928
50	33628
60	22765
70	15766
80	11148
90	8035
100	5893
110	4393

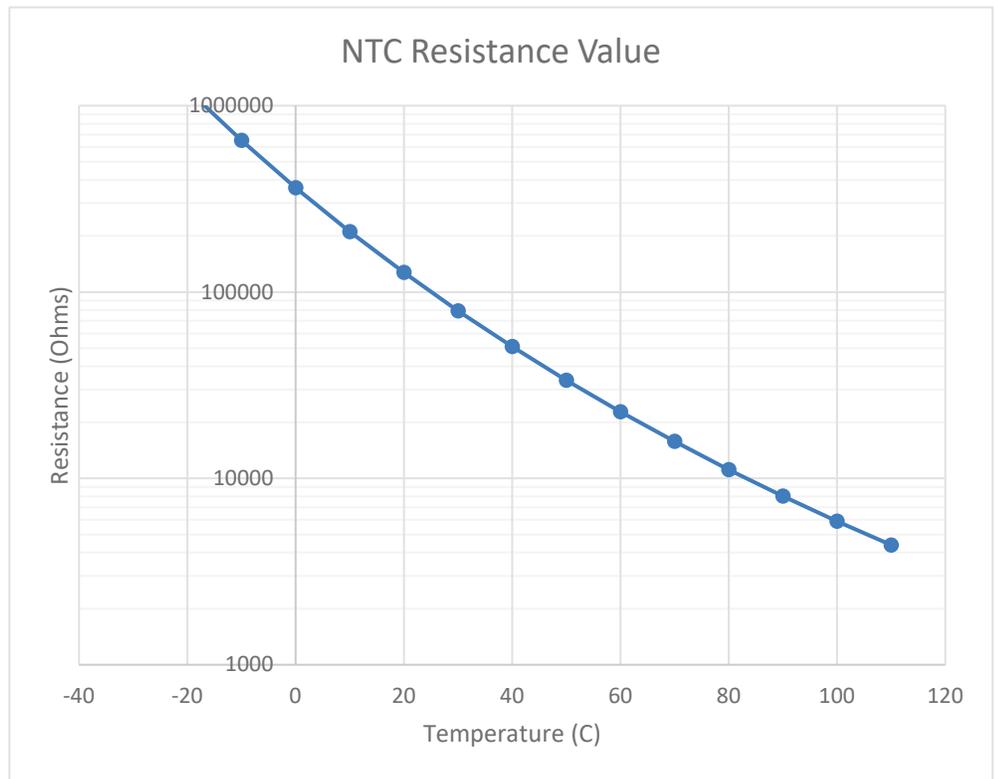


Figure 35 NTC Thermistor Resistance Curve (Logarithmic Scale)

HTRM Thermal Controller Temperature Set Point Example

Typical OCXO temperature set points are based on the turnover point of the crystal used.

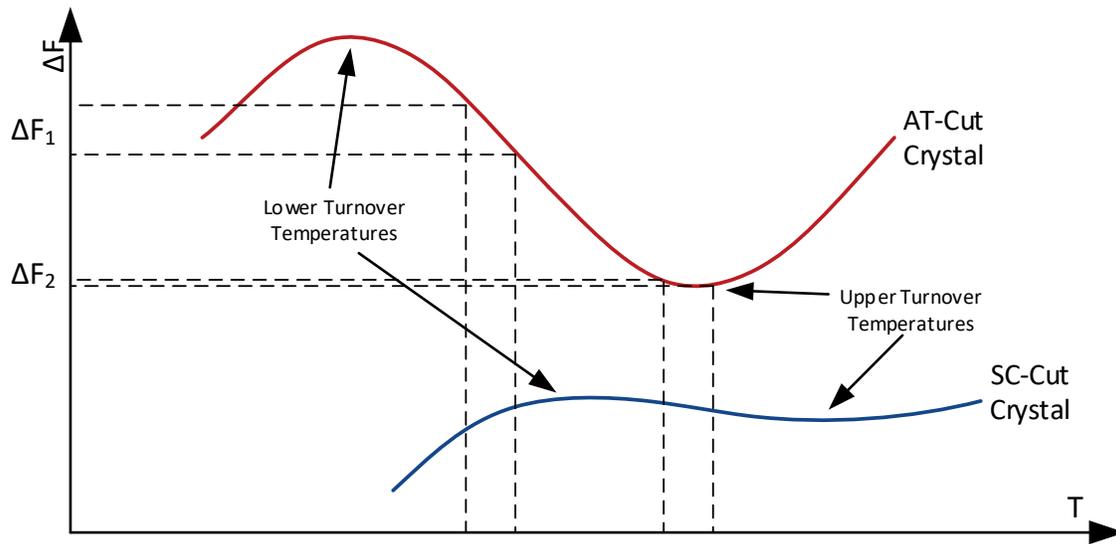


Figure 36 AT-cut and SC-cut Turnover Points

The TMx00 Control program's Thermal Setup tab provides an easy method to perform the initial thermal range setup based on the thermistor chosen and the temperature needed.

Assume for this example:

- 90C Target temperature set point
- 100k Ω at T_0 (25C) NTC
- 4170 Thermistor β

The circuit will be in thermal balance when the voltage at HTRM is approximately $BYPASS/2$ voltage. To configure the temperature set point, assume the Temp Set DAC (fine tuning) is adjusted to the midpoint voltage, or $BYPASS/2$ V. The current through R4 can then be assumed to be 0.

The resistance of a 100k Ω NTC thermistor with a β of 4170 at 90C is 8.181k Ω . Configure the value of the Thermal Range Resistor, R3, to this target resistance to determine the approximate middle point of the temperature set point range. The Temp Set DAC output voltage provides the high and low limits of the temperature set point adjustment range and is calculated within the software. When configuring R3, the TMx00 Control program will calculate the High, Center, and Low temperature range for that resistance. The target temperature set point must be within this range.

R3 is constructed with two banks of resistor values. Bank 1 of the Thermal Range Resistor must be individually selected. Bank 2 resistors may be selected in parallel with the first bank or individually to determine the R3 value. In this example, only selecting the 9k Ω resistor shows an estimated temperature range of 78.7 to 95.3 C, supporting the 90C target temperature.

Adjusting the Temp Set DAC value will provide the final temperature set point. This is determined by measuring the cavity temperature. Techniques for this measurement are described in the Application Notes section.

Alternately, the Thermal Range Resistor bank 1 can be set to OPEN and bank 2 resistors not selected. That allows an external resistor between HTRHM and BYPASS to replace R3 and provide a custom thermal range matching the thermistor resistance.

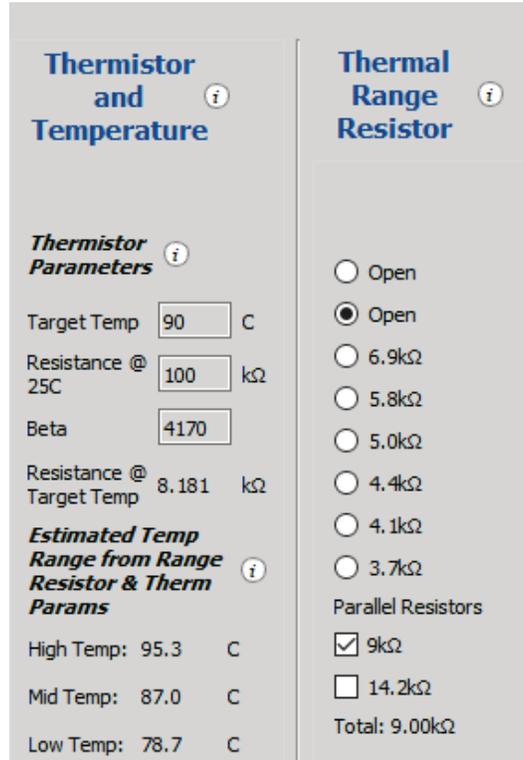


Figure 37 Thermal Range Settings in TMx00 Control Software

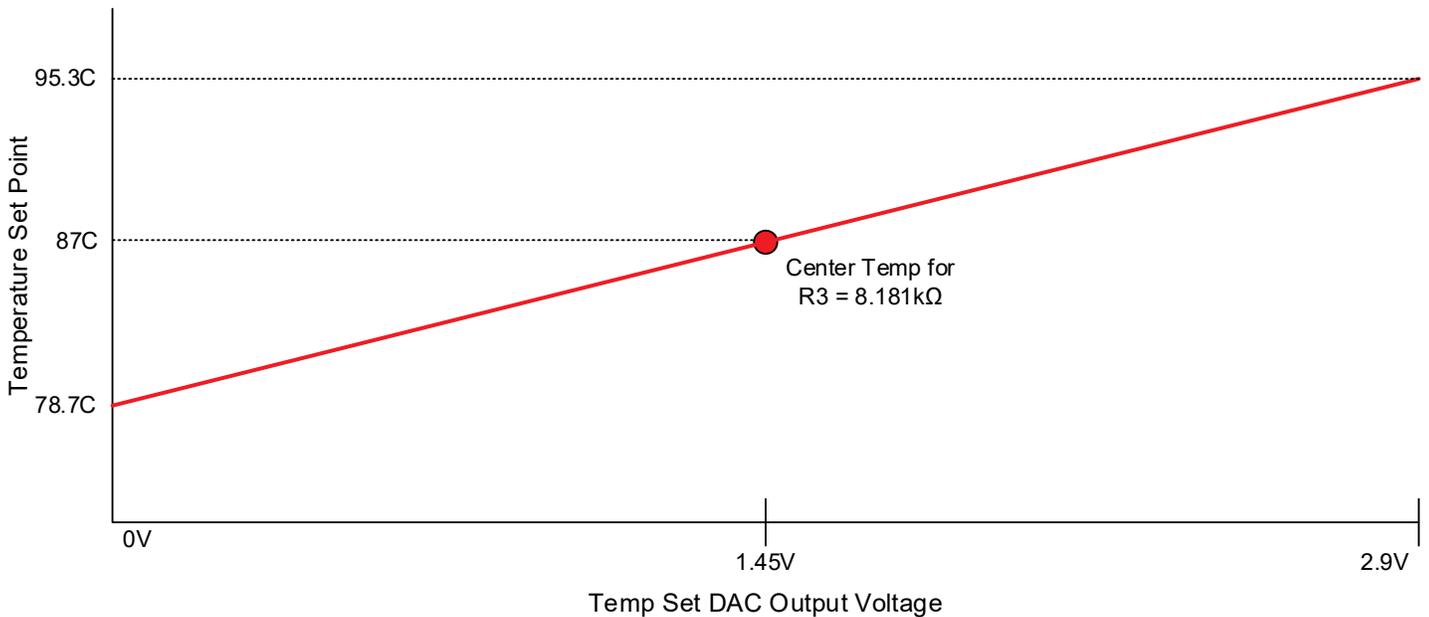


Figure 38 Approximate Temperature Set Point Range

External Thermal Range Resistor

An external resistor may be more desirable to use in place of the Thermal Range Resistor R3. Using an external resistor provides two opportunities:

1. *Extended temperature range* - The temperature range of the Thermal Controller can be moved downward to as low as -20C by replacing the 100kΩ NTC thermistor with one with a lower resistance at the reference temperature. 50kΩ, 25kΩ, or 10kΩ thermistors provide the needed range and require an external resistor value not within the range of internal resistor R3.
2. *Reduced Temperature Dependency* – The TM200 internal Thermal Range Resistor exhibits a small temperature dependency as the IC temperature fluctuates which results in the movement of the temperature set point. An external resistor without a temperature coefficient and a 1% tolerance eliminates this effect.

Implementing an external resistor requires setting R3 to OPEN and connecting the needed resistor between the BYPASS and HTHRM pins of the TM200 as shown below.

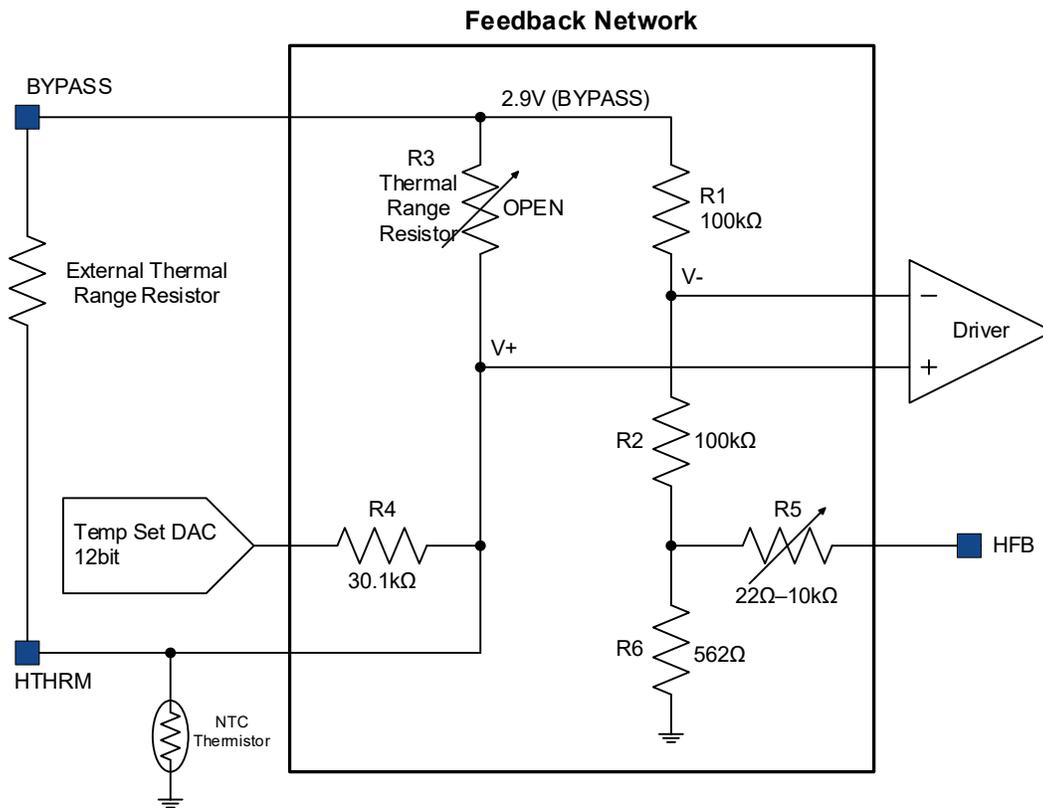


Figure 39 External Thermal Resistor Range Configuration

Cavity Temperature Measurement

The temperature of the thermal cavity needs to be verified in the initial design and setup phase. The cavity temperature is not read during normal closed loop thermal operation. This approach avoids any possibility of the measurement disrupting the thermal loop operation.

Methods to measure temperature during setup:

1. Connect MUX to the HTHRM terminal. Switch out R3 in the bridge and use an external precision resistor between HTHRM and BYPASS. This allows monitoring of the voltage on the thermistor terminal and thus the operating temperature of the cavity. Using the external precision resistor removes the tolerances of R3.
2. Use a separate thermistor or thermocouple to measure the cavity temperature. This technique has the benefit that the thermal loop is not disturbed during the setup.
3. Replace the AT or SC cut crystal with a Y cut crystal with a defined, high temperature coefficient. Measure the temperature by measuring the oscillator frequency with the manufacturer's calibration. This is a very sensitive measurement method. However, it does require a special crystal in the same package as the normal manufacturing one.
4. Characterize a production crystal over temperature use it for initial temperature calibration.

In production each OCXO will need to be characterized over ambient temperature to ensure the correct cavity temperature is achieved. That measurement process may eliminate the need for precision temperature measurement except for the initial cavity setup.

Thermal Time Constants

The size of the cavity and the thermal mass set the thermal time constant of the feedback loop and driving amplifier. The thermal time constant will indicate how fast the cavity shifts in temperature. All cavities have some thermal loss based on their thermal impedance to the outside environment.

The time constants and other thermal properties are difficult to compute without finite element or other thermal modeling software. In many cases these tools are not available to an OCXO designer.

The time constants and losses can be experimentally determined by closing the thermal feedback loop, starting from a lower temperature (usually room temperature) and observing the temperature and heater supply currents (HFB voltage) as the cavity heats up.

The TM200 includes a range of thermal feedback resistors that cover most cavity sizes. For smaller cavity sizes, start from the higher value feedback resistors. Observe the temperature over time to ensure the loop is not underdamped. Slightly overdamped is usually better. Then reduce the thermal feedback resistor until the underdamped condition. The best selection will usually be somewhere between one step and several steps toward a higher value.

Allan Deviation (Allan Variance)

All oscillators are noisy and exhibit phase noise mainly consisting of white noise and flicker noise. The flicker noise is also defined as $1/f$ noise. Moving lower in frequency the noise spectrum follows a $1/f^2$ curve, then a $1/f^3$ curve, continuing downward. Normal statistical analysis such as standard deviation will not converge as the time interval increases.

Dr. David W. Allan developed a statistical process (two sample variance) that allowed long term measurement of frequency stability in clocks (and other noisy physical processes). The Allan variance is defined as $\sigma_y^2(\tau)$, and the Allan deviation is the square root of the Allan variance, $\sigma_y(\tau)$.

The design and implementation of the TM200 was configured to show very low Allan deviation, with particular care for low noise in the flicker noise regime.

Measuring Allan deviation consists of a series of frequency measurements, without gaps, that are sampled using precise time intervals. The frequency measuring counter must contain the firmware needed to match the measurement requirements.

An effective analysis program is Stable32, available free of charge from IEEE-UFFC either on their website or from Github at IEEE-UFFC/stable32.

MCU Clock Source Selection

As mentioned in the Microcontroller Clock Source description, the MCU can be clocked using the internal ring oscillator within the TM200 or by the crystal oscillator itself. Upon startup, the MCU must be initially clocked by the internal ring oscillator because the crystal oscillator is not yet available. *However, the ring oscillator is noisy and asynchronous compared to the crystal oscillator, so it is advantageous to run the MCU from the crystal oscillator for better phase noise floor performance and less spurious energy.*

The TM200 is designed to have the MCU clock source switch over glitch-free from the ring oscillator to the crystal oscillator once it detects stable oscillator operation. This operation must be selected by the user otherwise the TM200 will continuously run off the ring oscillator. Please refer to the *TMx00 Control Software & EVB Kit Guide* for instructions on how to do this using the TMx00 Control Software and the *TMx00 Programming Reference Manual* for how to do this via I2C commands.

The MCU target clock speed is between 1 and 10 MHz, so internal frequency dividers can provide the proper clock rate for OCXO outputs exceeding 10MHz. If the crystal oscillator signal fails, the TM200 will automatically switch back to the ring oscillator so that MCU functionality and communication can be maintained.

External Thermistor (THRM Pin)

The THRM pin is an optional external thermistor input that replaces the internal temperature sensor to support direct monitoring of the crystal temperature. A typical circuit is shown in Figure 40. The thermistor has a negative temperature coefficient so the voltage on the THRM pin increases as the temperature increases. The voltage on the pin is scaled by the parallel resistor R0 and the series resistor R1.

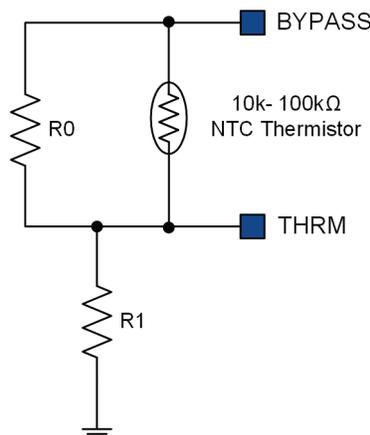


Figure 40 Typical External Thermistor Circuit

The resistance of Negative Temperature Coefficient thermistors is defined as:

$$R_T = R_0 * e^{\beta * (\frac{1}{T} - \frac{1}{T_0})}$$

Typical values for the thermistor R_0 are 10k, 20k, 50k, or 100k at 25 C. Beta values depend upon the manufacturer and type, with typical values of 3500 to 4500.

External Thermistor Implementation Example

Design Variables:

BYPASS = 2.9 Volts

Maximum Operating (correction) Temperature: 90 C

Minimum Operating (correction)Temperature: -40 C

Thermistor: $R_0@25\text{ C} = 100\text{k}$

Beta = 3.97k

Set R_0 and R_1 so that the maximum voltage at 90 C is 2.6 V. R_1 is the primary determinant of this voltage. This configuration allows good temperature step resolution at the high end and sufficient headroom for thermistor operation. Next set R_0 and R_1 (mostly R_0) so the minimum voltage is a few tenths of a volt. In this case the minimum voltage is 0.3V. The values selected are 806K Ω for R_0 and 80.6K Ω for R_1 .

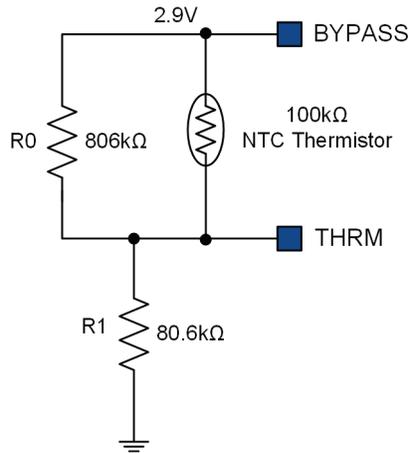


Figure 41 Thermistor Circuit Example

Figure 42 shows the resultant voltage curve over the operating temperature range. Note that the voltage is not a linear function of temperature. The firmware in the MCU properly handles the curvature so the proper DAC code can be sent to the Internal Varicap or external varactor for frequency tuning. Since the correction temperature range is reduced, the effective correction temperature step is also reduced.

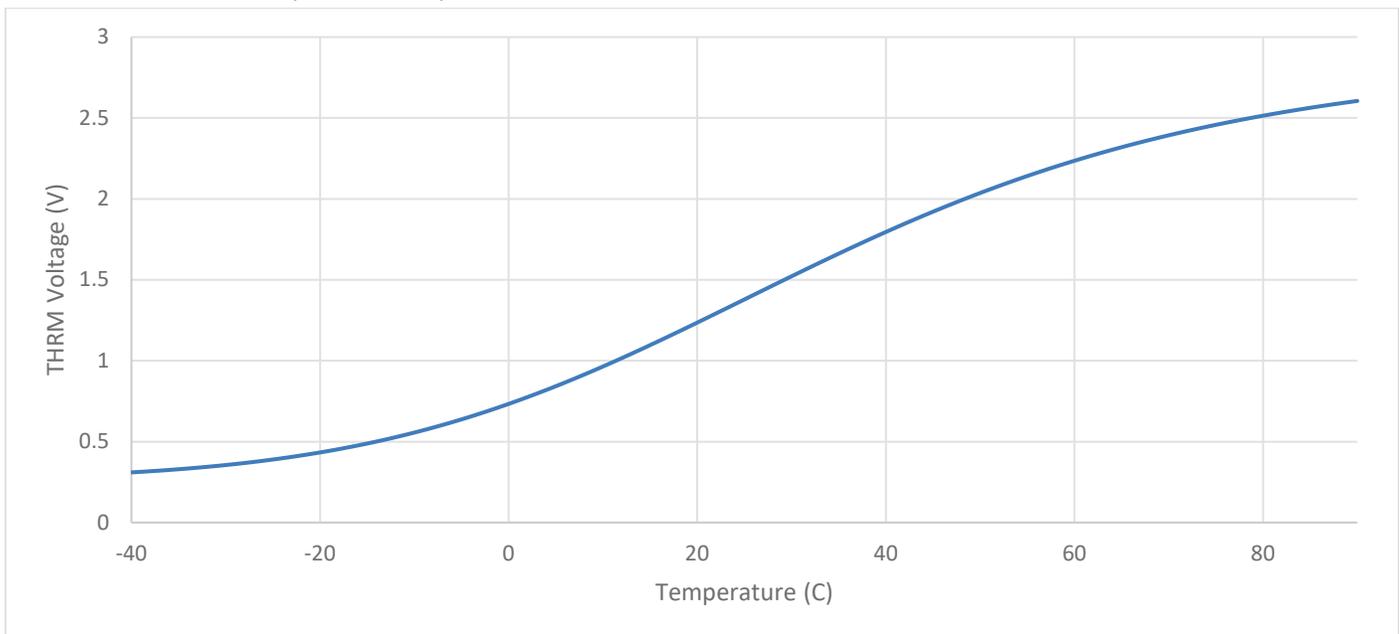


Figure 42 External Thermistor Circuit Transfer Curve

DESIGN EXAMPLE

The design example described below is one of many different possibilities as the TM200 supports many different types of oscillator architectures and OCXO module construction configurations. The example below is used to present one such configuration and its performance. This example uses a 20MHz fundamental AT-Cut crystal with the internal Varicap of the TM200, an unbuffered CMOS inverter output driver, and external thermistor for crystal temperature sensing.

Oscillator

The oscillator uses a 20MHz fundamental AT-Cut crystal with the internal Varicap and an unbuffered CMOS inverter output driver. This configuration can produce better phase noise floor performance by bypassing the additional stages in the RF Output Stage that provide increased functionality. Alternatively, output signal fanout and frequency division functionality with extremely low additive jitter can be achieved with the Hexius CF Series Fanout Buffers.

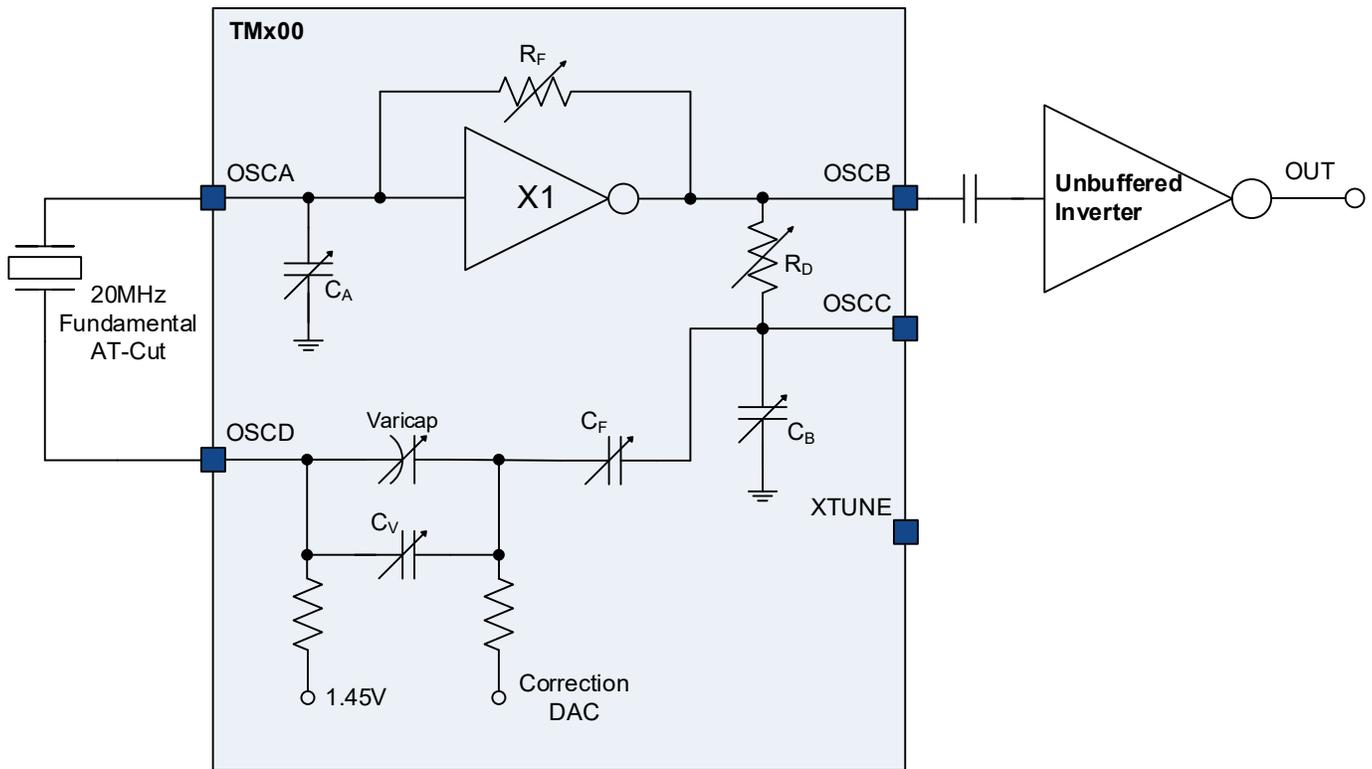


Figure 43 Oscillator Design Example

OCXO Module

An OCXO module can be constructed using the above oscillator design in the schematic shown below. The configuration uses a 100kΩ thermistor for the thermal controller loop and can use TM200’s internal temperature to provide additional crystal temperature monitor data. The module uses the TM200 internal heaters to control the oven temperature for a 9mm x 7mm enclosure. The oscillator supply (BYPASS) connects directly to VDD and an unbuffered inverter provides the best phase noise floor for the output signal. Note the bypass caps that should be used externally of the module.

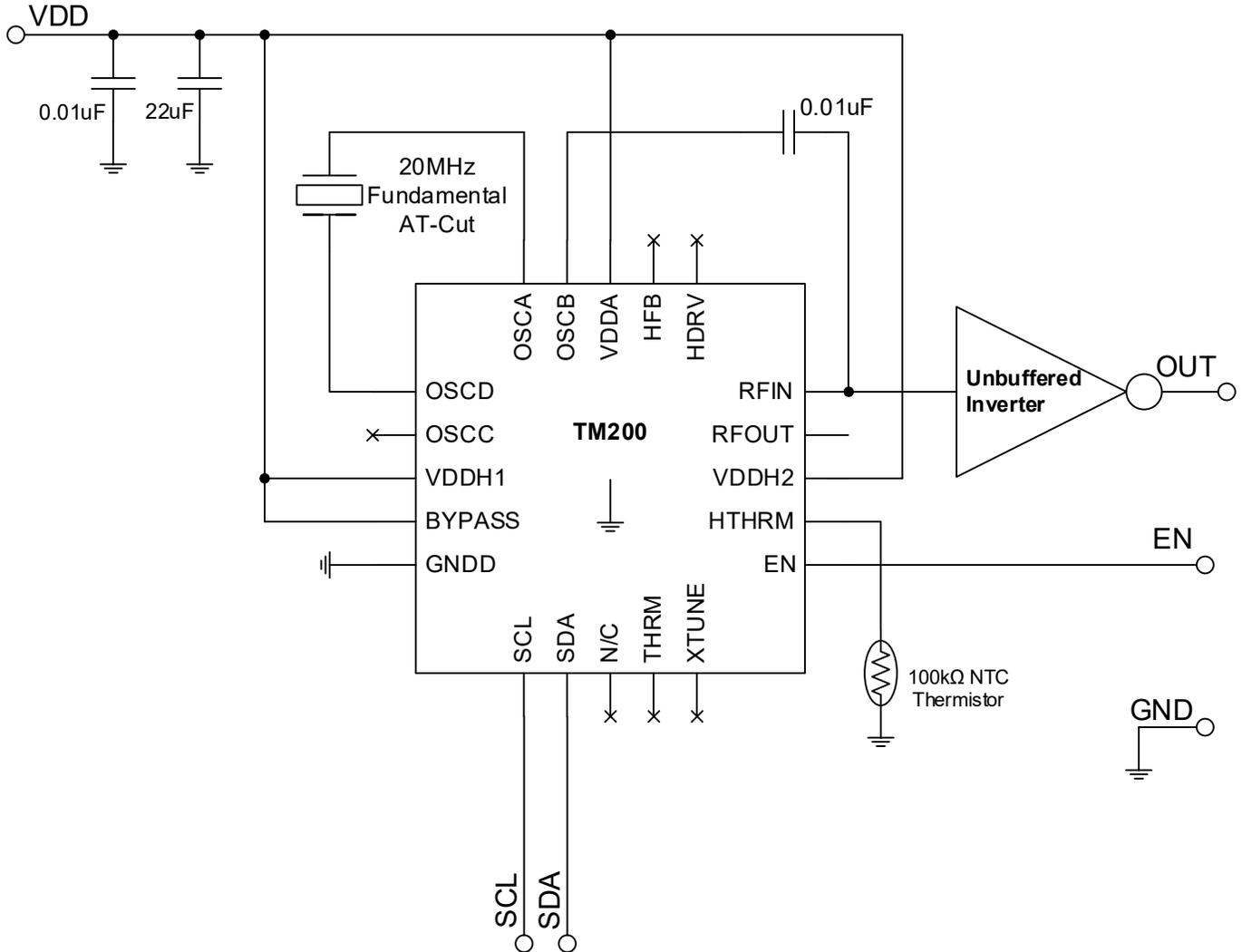


Figure 44 OCXO Module Design Example

Figure 45 OCXO Module example with a Fund AT-Cut crystal, Internal Heaters, Internal Varicap, RFOUT Stage and Internal Regulator

Phase Noise Performance

The oscillator configuration described above in conjunction with a 5032 20MHz crystal produces the following phase noise plot and is typical of many crystals. Many variables external to the TM200 contribute towards the phase noise performance of any oscillator and requires thoughtful design to meet an application’s specifications. Most of the spurs seen in plot below are artifacts of the Holzworth Phase Noise Analyzer and the evaluation board. This design example achieves an integrated jitter performance of 31fs and with a phase noise floor of roughly -175dBc/Hz. Updated and refined phase noise performance will be presented in future revisions of the datasheet and within the *TMx00 Design Example Manual*.

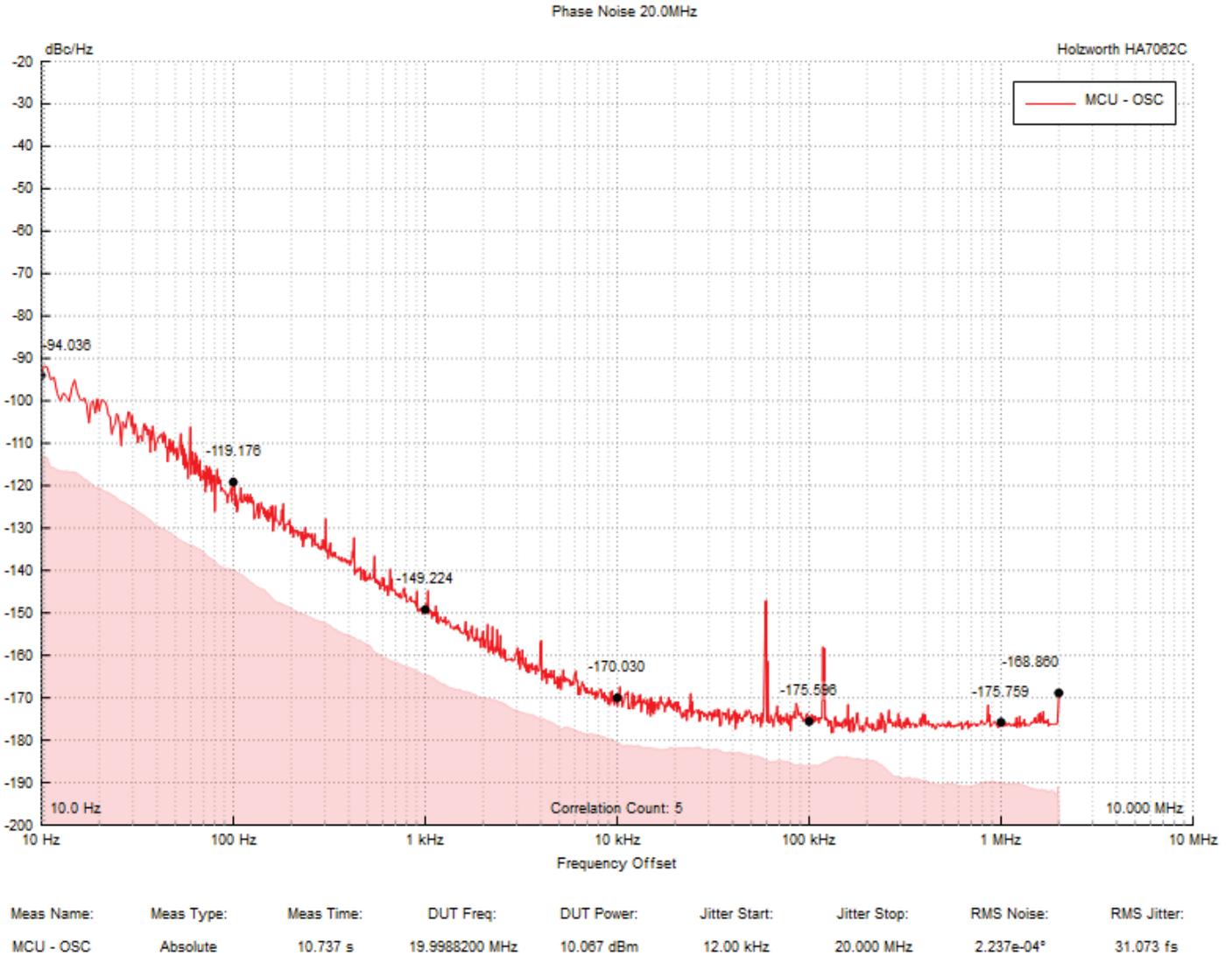


Figure 46 Phase Noise Performance

Frequency Stability

The TM200 has the ability to compensate for frequency variations across temperature below 10ppb with proper OCXO module construction, frequency-temperature characterization, and correction algorithm implementation. The IC provides the control and computational power to achieve very tight frequency stability performance, but the performance ultimately depends on the user’s ability to achieve tight thermal coupling and detailed characterization of a OCXO module design.

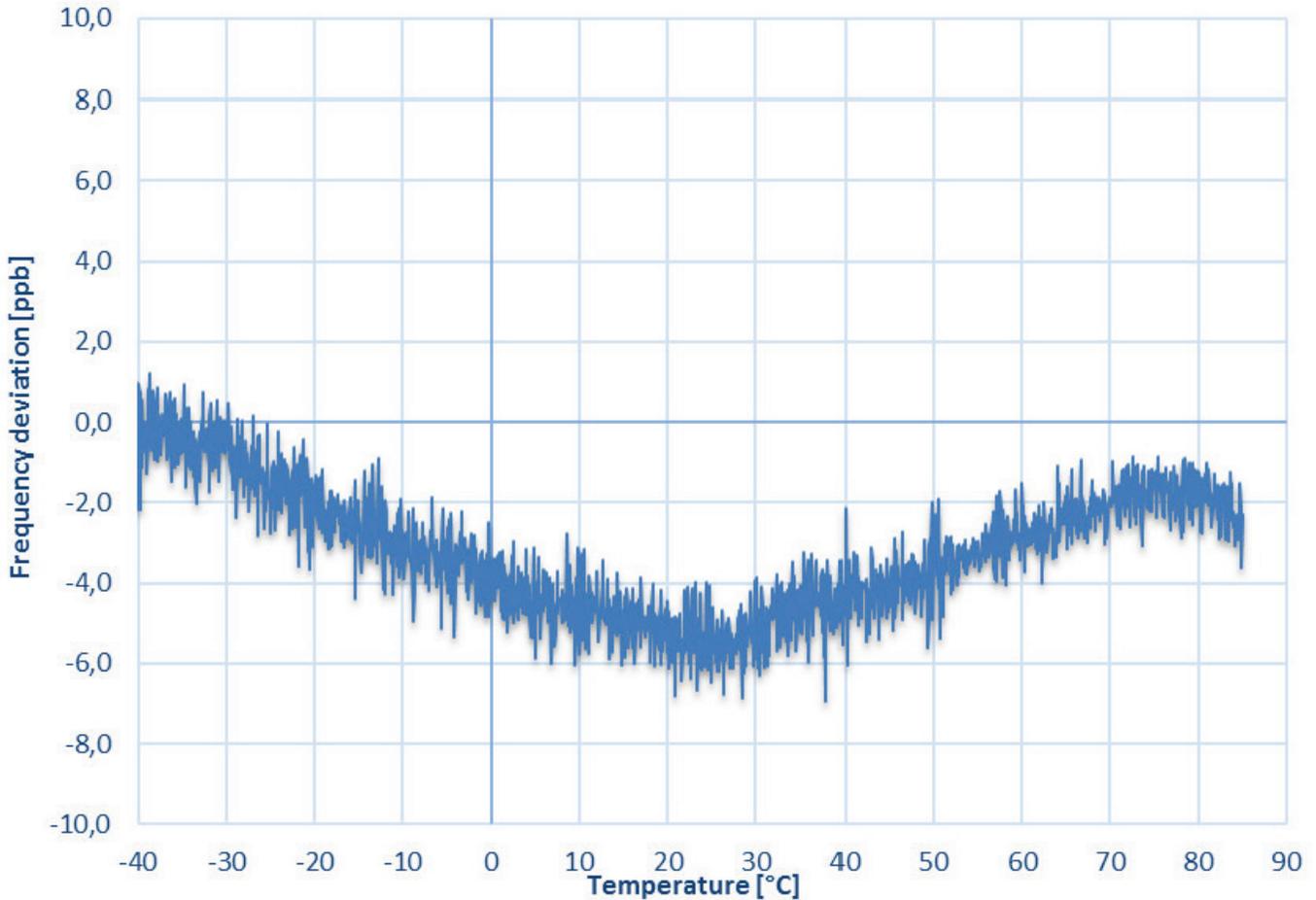


Figure 47 Frequency Stability Performance

Other Design Examples

Many other design examples are feasible with the TM200 to include 3OT crystals and various frequency ranges. Please refer to the *TMx00 Design Example Manual* for additional examples of various oscillator architectures that can be built with the TM200. The Hexius EB-TMx00 Evaluation board supports many of the possible options for rapid prototyping. Please contact Hexius Semiconductor for support in developing oscillator configurations and OCXO modules for your specific application.

PCB CONSIDERATIONS

Power Supply Filtering

On-chip regulation, power supply filtering and good PCB layout all contribute to minimizing power supply noise. For optimal performance the TM200 should be isolated from the power supply noise with the following guidelines:

1. Power supply traces need to be appropriately sized for the current demands.
2. Place a 22 μ F bypass capacitor from the power supply to the device's supply pins. An 0805 or larger X7R ceramic or tantalum capacitor is recommended.
3. One set of bypass capacitors values of 22 μ F, 0.1 μ F & 0.01 μ F should be placed as close as possible to the device.

Signal Traces

Improper routing of the signals of the TM200 can have adverse effects on the performance and therefore must be treated with care. Signals should not be treated as digital signals but rather high-performance RF analog signals otherwise system performance may be degraded. Signal routing guidelines include:

1. Physically locate the signal source as close to the load as possible
2. Limit the length of traces
3. Do not run signals through or near large FPGAs (or similar) with lots of switching activity and various frequencies
4. Do not run signals adjacent to digital data lines
5. Avoid routing signals near or alongside digital lines
6. Avoid crossing digital traces on an adjacent PCB planes
7. Shield signals with ground planes, adjacent traces, or both
8. Try to keep clock trace routes straight; if turns are necessary, make them with round bends

Table 12 Pad Coordinates

Pad	Pad Name	I/O/P	Description	X (um)	Y (um)	Bonded In Package
1	OSCA	I/O	Pierce inverter stage input from crystal	74.20	1797.04	Yes
2	VDDA	P	3.3V Analog Positive Supply	74.20	1712.80	No
3	GND A	P	Analog Ground	74.20	1628.56	No
4	OSCD	I/O	Crystal drive	74.20	1544.32	Yes
5	OSCC	I/O	Crystal drive	74.20	1460.08	Yes
6	GNDH	P	Heater Ground	74.20	1222.32	Yes
7	GNDH	P	Heater Ground	74.20	1138.08	Yes
8	VDDH1	P	3.3V Heater Supply	74.20	1053.84	Yes
9	VDDH1	P	3.3V Heater Supply	74.20	926.40	Yes
10	GNDH	P	Heater Ground	74.20	842.16	Yes
11	GNDH	P	Heater Ground	74.20	757.92	Yes
12	VDDA	P	3.3V Analog Positive Supply	74.20	435.92	No
13	GND A	P	Analog Ground	74.20	351.68	No
14	BYPASS	I/O	Oscillator Regulator Voltage (2.9V)	74.20	267.44	Yes
15	GND D	P	Digital Ground	74.20	183.20	Yes
16	SCL	I/O	I ² C Clock	183.20	74.20	Yes
17	SDA	I/O	I ² C Data	267.44	74.20	Yes
18	GND A	P	Analog Ground	699.52	74.20	No
19	VDDA	P	3.3V Analog Positive Supply	783.76	74.20	No
20	THRM	I	Thermistor Input	1468.56	74.20	Yes
21	GND D	P	Digital Ground	1552.79	74.20	No
22	XTUNE	O	Adjustable Tuning Voltage	1637.04	74.20	Yes
23	EN	I/O	Enable	1743.26	183.20	Yes
24	HTRM	I/O	Temperature Controller Thermistor	1743.26	267.44	Yes
25	GND A	P	Analog Ground	1743.26	351.68	No
26	VDDA	P	3.3V Analog Positive Supply	1743.26	435.92	No
27	GNDH	P	Heater Ground	1743.26	757.92	Yes
28	GNDH	P	Heater Ground	1743.26	842.16	Yes
29	VDDH2	P	3.3V Heater Supply	1743.26	926.40	Yes
30	VDDH2	P	3.3V Heater Supply	1743.26	1053.84	Yes
31	GNDH	P	Heater Ground	1743.26	1138.08	Yes
32	GNDH	P	Heater Ground	1743.26	1222.32	Yes
33	RFOUT_F	O	Fast RF Output - 3.3V	1743.26	1460.10	Yes
34	RFOUT_S	O	Slow RF Output - 3.3V	1743.26	1544.32	Yes
35	GND A	P	Analog Ground	1743.26	1628.56	No
36	VDDA	P	3.3V Analog Positive Supply	1743.26	1712.80	No
37	RFIN	I/O	Oscillator Input to Output Stage	1743.26	1797.04	Yes
38	HDRV	O	External Heater Driver	1637.04	1903.26	Yes
39	HFB	I/O	Heater Feedback	1552.80	1903.26	Yes
40	GND A	P	Analog Ground	952.24	1903.26	Yes
41	VDDA	P	3.3V Analog Positive Supply	868.00	1903.26	Yes
42	OSCB	I/O	Pierce Inverter Stage Output	267.44	1903.26	Yes

DIE Bonding Guidance

Bonding the TM200 die into a module will depend heavily on the circuit architecture that it is configured for. As a result, it is difficult to recommend a definitive bonding diagram for a die application. The packaged version of the TM200 is designed for maximum configurations but may not represent the optimum bonding for a specific module using the TM200. As a starting reference, Table 13 states which pads are bonded in the packaged version of the TM200.

Oscillator Pad Connections – Pads 1, 4, 5, 42

If the oscillator circuit of the TM200 is being used, OSCA (1) and OSCB (42) will need to be bonded. Bonding OSCC (5) and/or OSCD (4) will depend on the oscillator configuration and what TM200 internal devices are used. For example, if the internal Varicap of the TM200 is being used for the oscillator circuit, OSCD needs to be bonded.

Analog Power Supply (VDDA) – Pads 2, 12, 19, 26, 36, 41

The TM200 has multiple analog supply pads throughout the pad ring for robust ESD protection. Only one of these power supply pads need to be connected to power the 3.3V analog rail. The packaged version of the TM200 uses pad 41. Multiple pads may be connected.

Analog Ground Supply (GNDA) – Pads 3, 13, 18, 25, 35, 40

The TM200 has multiple analog ground pads throughout the pad ring for robust ESD protection. Only one of these power supply pads need to be connected to power the 0V analog rail. The packaged version of the TM200 uses pad 40. Multiple pads may be connected.

GNDH Pad Connections – Pads 6, 7, 10, 11 & Pads 27, 28, 31, 32

These pads support the internal heater functionality and need to be connected to ground. The packaged version of the TM200 bonds all the pads but only one on each side of the heater is required. For example, 6 & 10 or 7 & 9 for Heater 1 and 27 & 32 or 28 & 31 for Heater 2. GNDH may be shorted to GNDA outside of the IC.

VDDH Pad Connections – Pads 8,9 & Pads 29,30

These pads support the internal heater functionality and need to be connected. Both VDDH pads should be connected to split the high current requirements of the heater and provides reliability. VDDH may be shorted to VDD outside of the IC.

Digital Ground Supply (GNDD) – Pads 15, 21

Separating the digital ground from the analog ground is essential in reducing spurious energy so a separate ground exists that needs to be bonded. The packaged version only bonds pad 15 but bonding both pad 15 and 21 is a good idea. GNDD may be shorted to GNDA outside of the IC.

Communication Connections (SCL, SDA, EN) – Pads 16, 17, 23

SCL and SDA must be bonded to have I²C communication with the IC. EN may be connected to control the enable function. Alternatively, it may be left unbonded and subsequently pulled to a logic HIGH via an internal pullup.

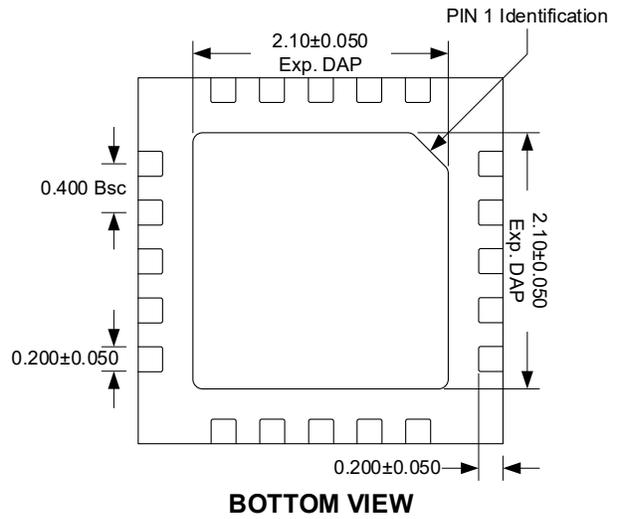
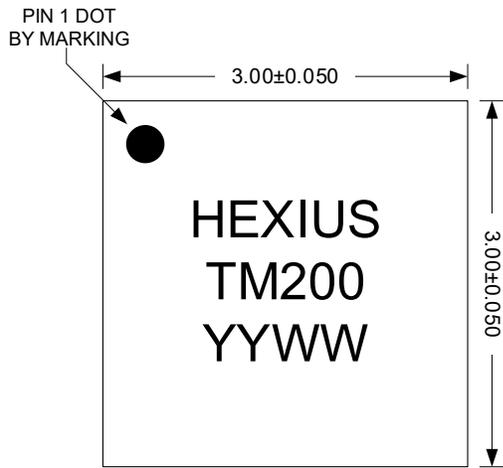
Optional Functionality – Pads 20, 22

XTUNE & THRM are pads for optional functionality. XTUNE needs to be bonded if an external varactor is being used. THRM needs to be bonded to use an external thermistor for additional temperature measurement.

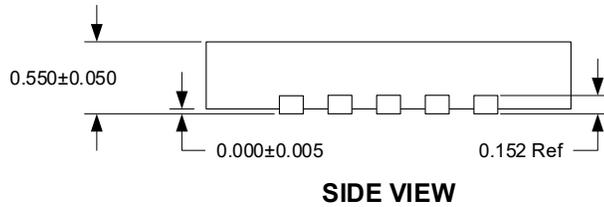
RFOUT Options – Pads 33, 34

The TM200 RFOUT Output Stage has two driver options to produce different edge rates. Depending on the application, one driver can be bonded instead of the other. However, the driver circuits can be bonded together (shorted) and individually selected via the control software. The packaged version of the TM200 shorts pad 33 and 34 to the RFOUT pin.

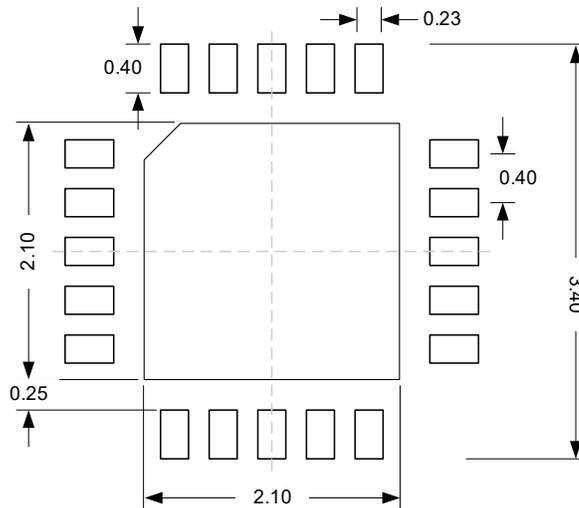
Package Outline



All units are in millimeters



PCB LAND PATTERN/FOOTPRINT





For more information about all Hexius Semiconductor products visit our website at

www.hexiussemi.com



The information in this document is believed to be accurate in all respects at the time of publication but is subject to change without notice. Hexius Semiconductor assumes no responsibility for errors and omissions and disclaims responsibility for any consequences resulting from the use of information included herein. Additionally, Hexius Semiconductor assumes no responsibility for the functioning of undescribed features or parameters. Hexius Semiconductor reserves the right to make changes without further notice. Hexius Semiconductor makes no warranty, representation or guarantee regarding the suitability of its products for any particular purpose, nor does Hexius Semiconductor assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation consequential or incidental damages. Hexius Semiconductor products are not designed, intended, or authorized for use in applications intended to support or sustain life, or for any other application in which the failure of the Hexius Semiconductor product could create a situation where personal injury or death may occur. Should Buyer purchase or use Hexius Semiconductor products for any such unintended or unauthorized application, Buyer shall indemnify and hold Hexius Semiconductor harmless against all claims and damages.