

LDC1041: 8-bit Rp, 24-bit L Inductance-to-Digital Converter with SPI

1 Features

- Remote sensor placement (decoupling the LDC from harsh environments)
- High durability (by virtue of contactless operation)
- Higher flexibility for system design (using coils or springs as sensors)
- Insensitive to non-conductive environmental interferers (such as dirt, dust, oil etc.)
- Magnet-free operation
- Sub-micron precision
- Supply Voltage: 5 V, typ
- Supply voltage, IO: 1.8V to 5.5V
- Stand-by current: 250uA, typ
- Rp resolution: 8-bit
- L resolution: 24-bit
- LC frequency range: 5kHz to 5MHz

2 Applications

- Level sensing
- Proximity sensing
- Spring motion sensing
- Lateral and angular position sensing
- Metal composition detection

3 Description

Inductive sensing is a contactless, short-range sensing technology enabling high-resolution and low-cost position sensing of conductive targets, even in harsh environments. Using a coil or spring as a sensor, the LDC1041 inductance-to-digital converter provides system designers a way to achieve high performance and reliability at a lower system cost than other competing solutions.

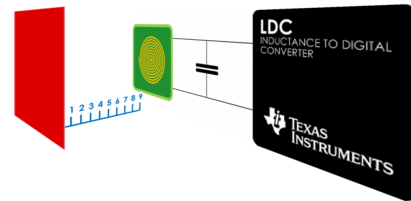
The LDC1041 is pin compatible with the LDC1000 (16-bit Rp/24-bit L) and the LDC1051 (8-bit Rp). This family of devices offers system designers different resolution options based on their application and system requirements.

The LDC1041 is available in a 5mm x 4mm WSON-16 package. Device programming via SPI allows for easy configuration using a microcontroller.

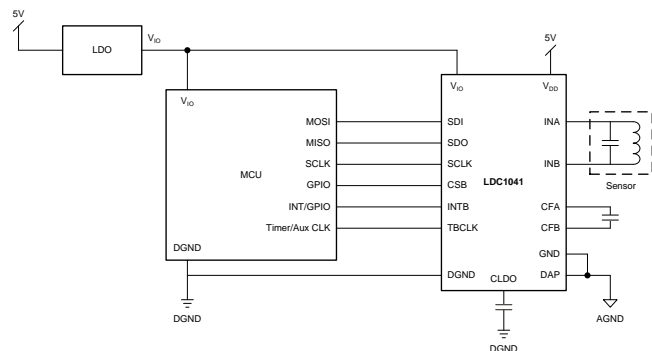
Device Information

| ORDER NUMBER | PACKAGE | BODY SIZE |
|--------------|-----------|-------------|
| LDC1041NHRT | WSON (16) | 5 mm x 4 mm |
| LDC1041NHRR | WSON (16) | 5 mm x 4 mm |
| LDC1041NHRJ | WSON (16) | 5 mm x 4 mm |

Axial Distance Sensing Application



Application Schematic



Rp vs Distance With 14mm PCB Coil

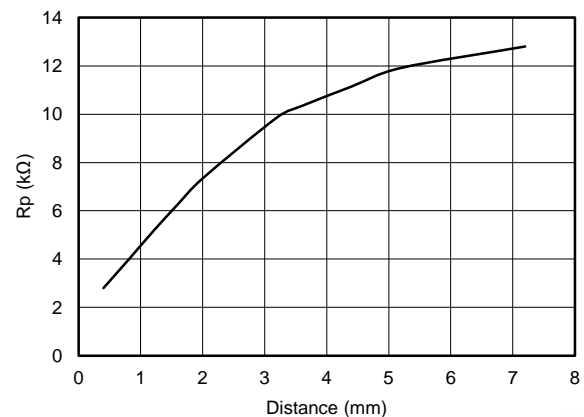


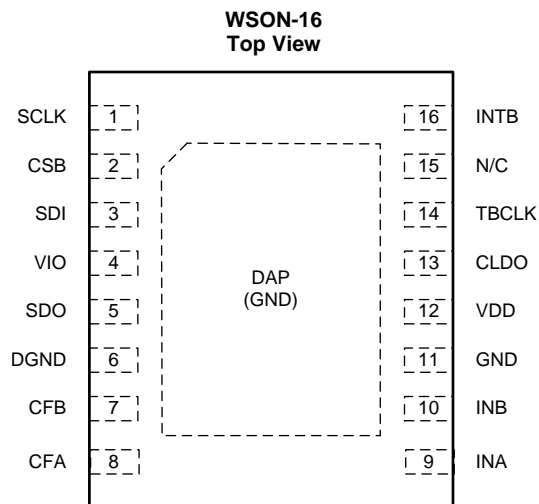
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4 Revision History

| DATE | REVISION | NOTES |
|------------|----------|------------------|
| March 2014 | * | Initial release. |

5 Terminal Configuration and Functions



Terminal Description

| TERMINAL NAME | TERMINAL NO. | TERMINAL TYPE ⁽¹⁾ | FUNCTION |
|---------------|--------------|------------------------------|---|
| SCLK | 1 | DO | SPI clock input. SCLK is used to clock-out/clock-in the data from/into the chip |
| CSB | 2 | DI | SPI CSB(Chip Select Bar). Multiple devices can be connected on the same SPI bus and CSB can be used to select the device to be communicated with |
| SDI | 3 | DI | SPI Slave Data In (Master Out Slave In). This should be connected to the Master Out Slave In of the master |
| VIO | 4 | P | Digital IO Supply |
| SDO | 5 | DO | SPI Slave Data Out (Master In Slave Out).It is high impedance when CSB is high |
| DGND | 6 | P | Digital ground |
| CFB | 7 | A | LDC filter capacitor |
| CFA | 8 | A | LDC filter capacitor |
| INA | 9 | A | External LC Tank. Connect to external LC tank |
| INB | 10 | A | External LC Tank. Connect to external LC tank |
| GND | 11 | P | Analog ground |
| VDD | 12 | P | Analog supply |
| CLDO | 13 | A | LDO bypass capacitor. A 56nF capacitor should be connected from this Terminal to GND |
| TBCLK | 14 | DI | External time-base clock |
| N/C | 15 | N/C | No Connection |
| INTB | 16 | DO | Configurable interrupt. This Terminal can be configured to behave in 3 different ways by programing the INT Terminal mode register. Either threshold detect, wakeup, or DRDYB |
| DAP | 17 | P | Connect to GND |

(1) DO: Digital Output, DI: Digital Input, P: Power, A: Analog

6 Specifications

6.1 Absolute Maximum Ratings⁽¹⁾

| | MIN | MAX | UNIT |
|--|------|----------------|------|
| Analog Supply Voltage ($V_{DD} - GND$) | | 6 | V |
| IO Supply Voltage ($V_{IO} - GND$) | | 6 | V |
| Voltage on any Analog Terminal | -0.3 | $V_{DD} + 0.3$ | V |
| Voltage on any Digital Terminal | -0.3 | $V_{IO} + 0.3$ | V |
| Input Current on INA and INB | | 8 | mA |
| Junction Temperature, T_J ⁽²⁾ | | 150 | °C |

- (1) Absolute Maximum Ratings are limits beyond which damage to the device may occur. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability. Operating Ratings are conditions under which operation of the device is intended to be functional. For ensured specifications and test conditions, see the Electrical Characteristics.
- (2) The maximum power dissipation is a function of $T_J(MAX)$, θ_{JA} , and the ambient temperature, T_A . The maximum allowable power dissipation at any ambient temperature is $P_{D(MAX)} = (T_J(MAX) - T_A) / \theta_{JA}$. All numbers apply for packages soldered directly onto a PC board. The package thermal impedance is calculated in accordance with JESD 51-7.

6.2 Handling Ratings

| | | MIN | MAX | UNIT |
|--------------------------|---|-----|-----|------|
| T_{stg} | Storage Temperature Range | -65 | 150 | °C |
| V_{ESD} ⁽¹⁾ | Human Body Model (HBM) ESD stress voltage ⁽²⁾ | 1k | 1k | V |
| | Charge Device Model (CDM) ESD stress voltage ⁽³⁾ | 250 | 250 | V |

- (1) Electrostatic discharge (ESD) to measure device sensitivity and immunity to damage caused by assembly line electrostatic discharges in to the device.
- (2) Level listed above is the passing level per ANSI, ESDA, and JEDEC JS-001. JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
- (3) Level listed above is the passing level per EIA-JEDEC JESD22-C101. JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions⁽¹⁾

over operating free-air temperature range (unless otherwise noted)

| | MIN | MAX | UNIT |
|--|------|------|------|
| Analog Supply Voltage ($V_{DD} - GND$) | 4.75 | 5.25 | V |
| IO Supply Voltage ($V_{IO} - GND$) | 1.8 | 5.25 | V |
| $V_{DD} - V_{IO}$ | 0 | | V |
| Operating Temperature, T_A | -40 | 125 | °C |

- (1) Absolute Maximum Ratings are limits beyond which damage to the device may occur. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability. Operating Ratings are conditions under which operation of the device is intended to be functional. For ensured specifications and test conditions, see the Electrical Characteristics.

6.4 Thermal Information

| THERMAL METRIC ⁽¹⁾ | | NHR (16-TERMINALS) | UNIT |
|-------------------------------|--|-----------------------|------|
| θ_{JA} | Junction-to-ambient thermal resistance | 28 | °C/W |

- (1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, [SPRA953](#).

6.5 Electrical Characteristics⁽¹⁾

Unless otherwise specified, all limits ensured for $T_A = T_J = 25^\circ\text{C}$, $V_{DD} = 5\text{ V}$, $V_{IO} = 3.3\text{ V}$ ⁽²⁾

| PARAMETER | | TEST CONDITIONS | MIN ⁽³⁾ | TYP ⁽⁴⁾ | MAX ⁽³⁾ | UNIT |
|------------------------------------|-----------------------------------|--|---------------------|------------------------------|---------------------|----------------|
| POWER | | | | | | |
| V_{DD} | Analog supply voltage | | 4.75 | 5 | 5.25 | V |
| V_{IO} | IO supply voltage | $V_{IO} \leq V_{DD}$ | 1.8 | 3.3 | 5.25 | V |
| I_{DD} | Supply current, V_{DD} | Does not include sensor current. ⁽⁵⁾ | | 1.7 | 2.3 | mA |
| I_{VIO} | IO supply current | Static current | | | 14 | μA |
| I_{DD_LP} | Stand-by mode supply current | | | 250 | | μA |
| t_{START} | Start-Up Time | From POR to ready-to-convert. | | 2 | | ms |
| LDC | | | | | | |
| f_{sensor_MIN} | Minimum sensor frequency | | | 5 | | kHz |
| f_{sensor_MAX} | Maximum sensor frequency | | | 5 | | MHz |
| A_{sensor_MIN} | Minimum sensor amplitude | | | 1 | | V_{PP} |
| A_{sensor_MAX} | Maximum sensor amplitude | | | 4 | | V_{PP} |
| t_{REC} | Recovery time | Oscillation start-up time after Rp under-range condition | | 10 | | $1/f_{sensor}$ |
| Rp Min | Minimum sensor Rp range | | | 798 | | Ω |
| Rp Max | Maximum Sensor Rp range | | | 3.93 | | M Ω |
| Rp Res | Rp measurement resolution | | | 8 | | Bits |
| L Res | Inductance measurement resolution | | | 24 | | Bits |
| t_{S_MIN} | Minimum response time | Minimum programmable settling time of digital filter | | $192 \times 1 / f_{sensor}$ | | s |
| t_{S_MAX} | Maximum response time | Maximum programmable settling time of digital filter | | $6144 \times 1 / f_{sensor}$ | | s |
| EXTERNAL CLOCK | | | | | | |
| f | External clock frequency | | | | 8 | MHz |
| DIGITAL I/O CHARACTERISTICS | | | | | | |
| V_{IH} | Logic 1 input voltage | | $0.8 \times V_{IO}$ | | | V |
| V_{IL} | Logic 0 input voltage | | | | $0.2 \times V_{IO}$ | V |
| V_{OH} | Logic 1 output voltage | $I_{SOURCE} = 400\ \mu\text{A}$ | | $V_{IO} - 0.3$ | | V |
| V_{OL} | Logic 0 output voltage | $I_{SINK} = 400\ \mu\text{A}$ | | | 0.3 | V |
| I_{IOHL} | Digital IO leakage current | | -500 | | 500 | nA |

- Electrical Characteristics Table values apply only for factory testing conditions at the temperature indicated. Factory testing conditions result in very limited self-heating of the device such that $T_J = T_A$. No specification of parametric performance is indicated in the electrical tables under conditions of internal self-heating where $T_J > T_A$. Absolute Maximum Ratings indicate junction temperature limits beyond which the device may be permanently degraded, either mechanically or electrically.
- The maximum power dissipation is a function of $T_J(\text{MAX})$, θ_{JA} , and the ambient temperature, T_A . The maximum allowable power dissipation at any ambient temperature is $P_{D\text{MAX}} = (T_J(\text{MAX}) - T_A) / \theta_{JA}$. All numbers apply for packages soldered directly onto a PC board. The package thermal impedance is calculated in accordance with JESD 51-7.
- Limits are specified by testing, design, or statistical analysis at 25°C . Limits over the operating temperature range are specified through correlations using statistical quality control (SQC) method.
- Typical values represent the most likely parametric norm as determined at the time of characterization. Actual typical values may vary over time and will also depend on the application and configuration. The typical values are not tested and are not specified on shipped production material.
- LC tank current depends on the Q-factor of the tank, distance and material of the target.

6.6 Timing Requirements

Unless otherwise noted, all limits specified at $T_A = 25^\circ\text{C}$, $V_{DD} = 5$, $V_{IO} = 3.3$, 10 pF capacitive load in parallel with a 10 kΩ load on the SDO terminal. Specified by design; not production tested.

| PARAMETER | | | MIN | TYP | MAX | UNIT |
|-------------|-----------------------------|--|------------------|-------------------------|-----|------|
| f_{SCLK} | Serial Clock Frequency | | | | 4 | MHz |
| t_{PH} | SCLK Pulse Width High | $f_{SCLK} = 4 \text{ MHz}$ | $0.4 / f_{SCLK}$ | | | s |
| t_{PL} | SCLK Pulse Width Low | $f_{SCLK} = 4 \text{ MHz}$ | $0.4 / f_{SCLK}$ | | | s |
| t_{SU} | SDI Setup Time | | 10 | | | ns |
| t_H | SDI Hold Time | | 10 | | | ns |
| t_{ODZ} | SDO Driven-to-Tristate Time | Measured at 10% / 90% point | | | 20 | ns |
| t_{OZD} | SDO Tristate-to-Driven Time | Measured at 10% / 90% point | | | 20 | ns |
| t_{OD} | SDO Output Delay Time | | | | 20 | ns |
| t_{CSS} | CSB Setup Time | | 20 | | | ns |
| t_{CSH} | CSB Hold Time | | 20 | | | ns |
| t_{IAG} | Inter-Access Gap | | 100 | | | ns |
| t_{DRDYB} | Data ready pulse width | Data ready pulse at every 1 / ODR if no data is read | | $1 / f_{\text{sensor}}$ | | s |

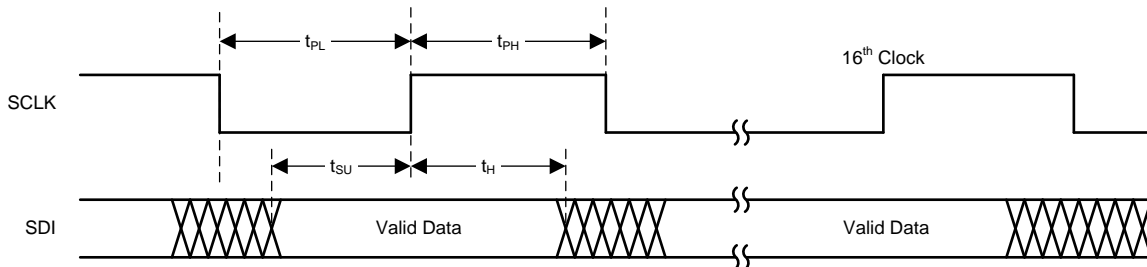


Figure 1. Write Timing Diagram

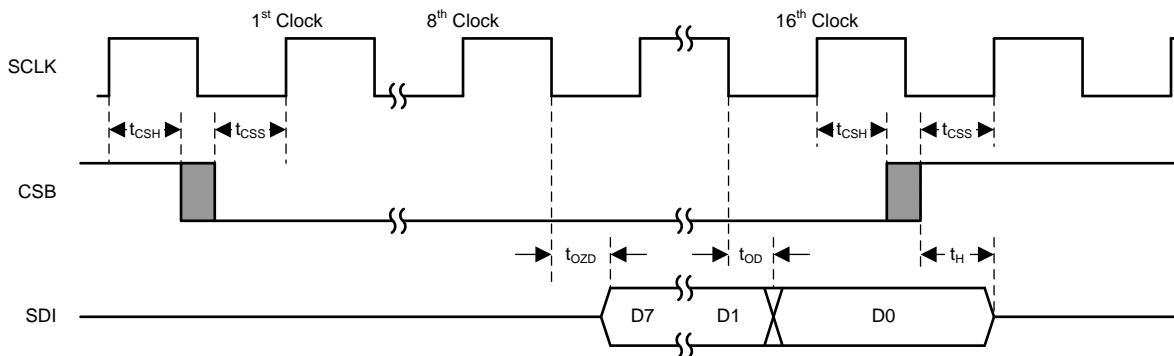
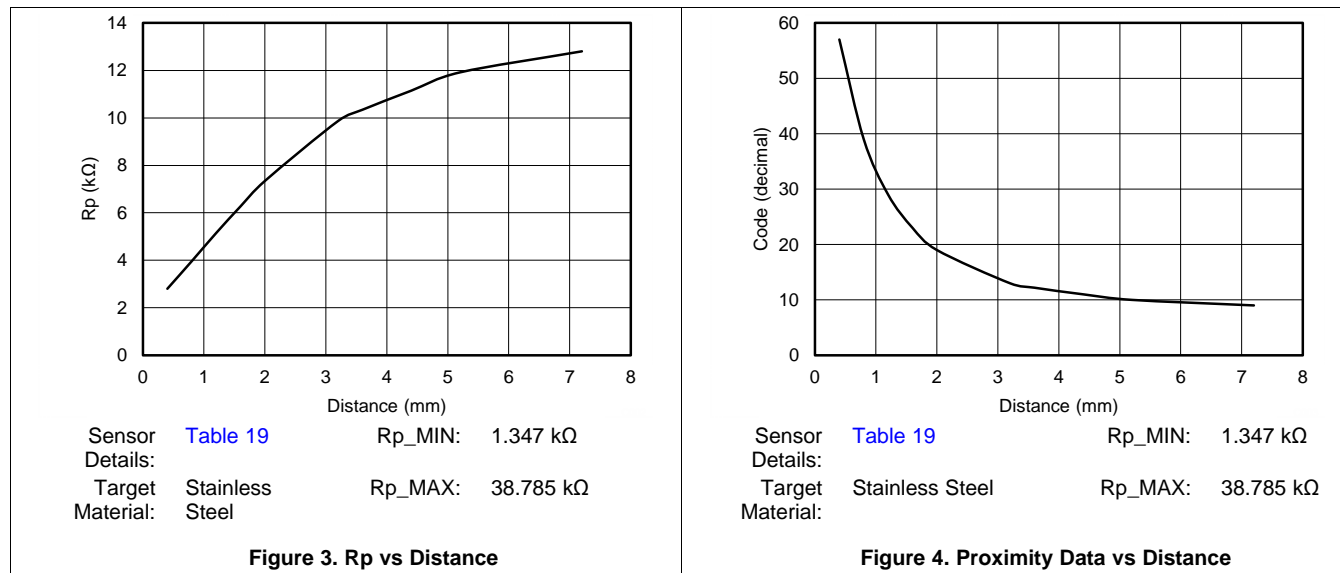


Figure 2. Read Timing Diagram

6.7 Typical Characteristics



7 Detailed Description

7.1 Overview

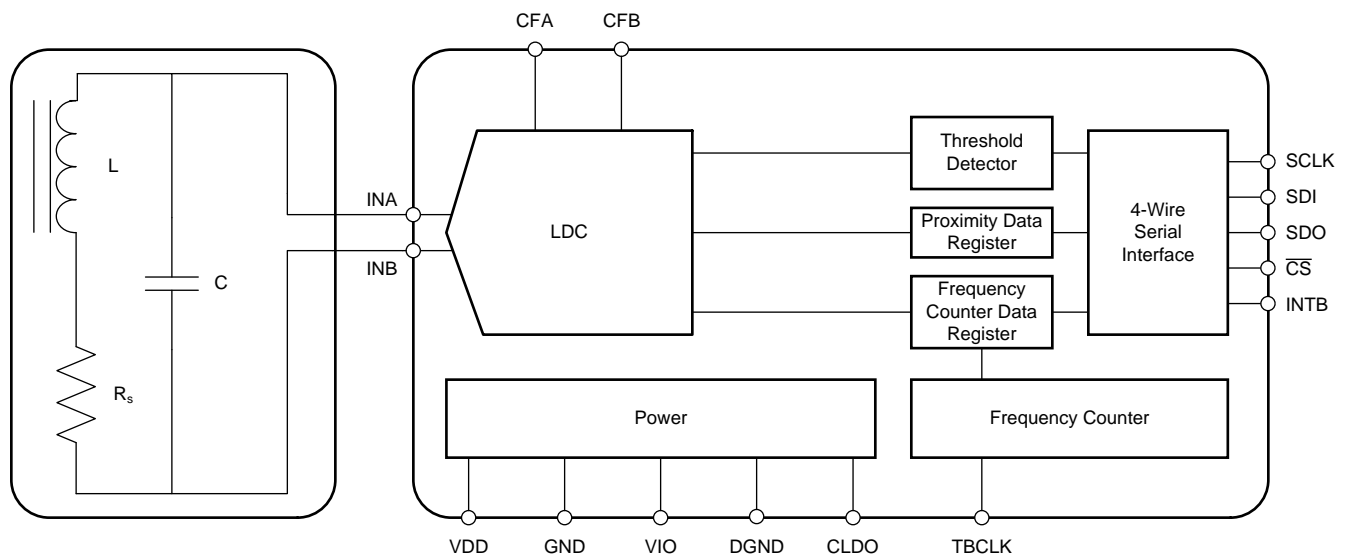
The LDC1041 is an Inductance-to-Digital Converter that simultaneously measures the impedance and resonant frequency of an LC resonator. It accomplishes this task by regulating the oscillation amplitude in a closed loop configuration to a constant level, while monitoring the energy dissipated by the resonator. By monitoring the amount of power injected into the resonator, the LDC1041 can determine the value of R_p ; it returns this as a digital value which is inversely proportional to R_p . In addition, the LDC1041 also measure the oscillation frequency of the LC circuit; this frequency is used to determine the inductance of the LC circuit. The device outputs a digital value that is inversely proportional to frequency.

The threshold detector block provides a comparator with hysteresis, with the threshold registers programmed and comparator enabled, proximity data register is compared with threshold registers and INTB pin indicates the output.

The device has a simple 4-wire SPI interface. The INTB pin provides multiple functions which are programmable with SPI.

The device has separate supplies for Analog and I/O, with analog operating at 5V and I/O at 1.8-5V. The integrated LDO needs a 56nF capacitor connected from CLDO pin to GND.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 Inductive Sensing

An AC current flowing through a coil will generate an AC magnetic field. If a conductive material, such as a metal target, is brought into the vicinity of the coil, this magnetic field will induce circulating currents (eddy currents) on the surface of the target. These eddy currents are a function of the distance, size, and composition of the target. The eddy currents then generate their own magnetic field, which opposes the original field generated by the coil. This mechanism is best compared to a transformer, where the coil is the primary core and the eddy current is the secondary core. The inductive coupling between both cores depends on distance and shape. Hence the resistance and inductance of the secondary core (eddy current), shows up as a distant dependent resistive and inductive component on the primary side (coil). [Figure 5](#) to [Figure 8](#) show a simplified circuit model.

Feature Description (continued)

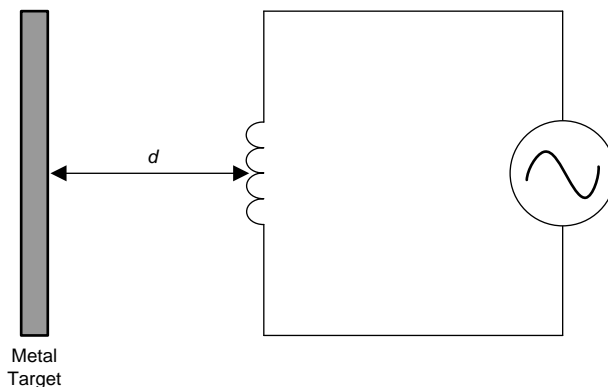


Figure 5. Inductor With A Metal Target

Eddy currents generated on the surface of the target can be modeled as a transformer as shown in Figure 6. The coupling between the primary and secondary coils is a function of the distance and the conductor's characteristics. In Figure 6, the inductance L_s is the coil's inductance, and R_s is the coil's parasitic series resistance. The inductance $L(d)$, which is a function of distance d , is the coupled inductance of the metal target. Likewise, $R(d)$ is the parasitic resistance of the eddy currents and is also a function of distance.

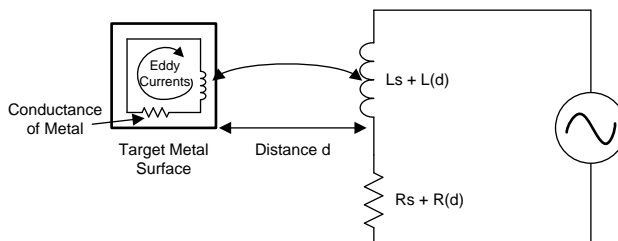


Figure 6. Metal Target Modeled As L And R With Circulating Eddy Currents

Generating an alternating magnetic field with just an inductor will consume a large amount of power. This power consumption can be reduced by adding a parallel capacitor, turning it into a resonator as shown in Figure 7. In this manner the power consumption is reduced to the eddy and inductor losses $R_s + R(d)$ only.

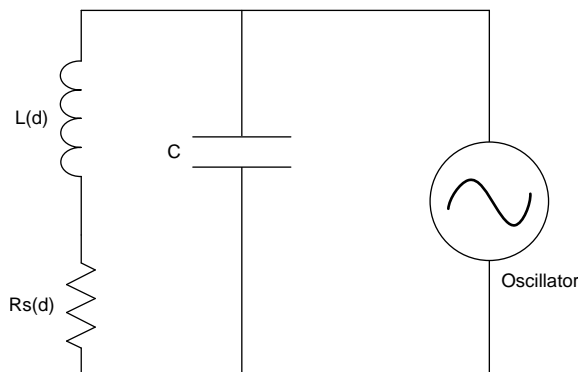


Figure 7. LC Tank Connected To Oscillator

The LDC1041 doesn't measure the series resistance directly; instead it measures the equivalent parallel resonance impedance R_p (see Figure 8). This representation is equivalent to the one shown in Figure 8, where the parallel resonance impedance $R_p(d)$ is given by:

Feature Description (continued)

$$R_p(d) = \frac{L_s + L(d)}{[R_s + R(d)] \times C} \tag{1}$$

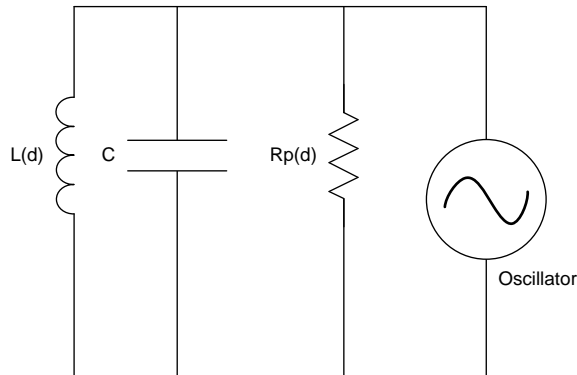


Figure 8. Equivalent Resistance Of Rs in Parallel With LC Tank

Figure 9 below shows the variation in Rp as a function of distance for a 14mm diameter PCB coil (Sensor Details: Table 19). The target in this example is a section of a 2mm thick stainless steel disk.

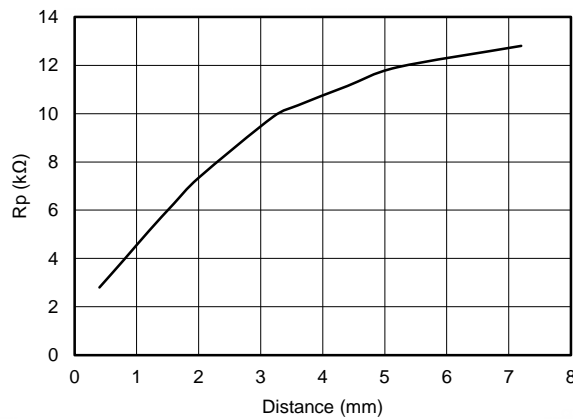


Figure 9. Typical Rp vs Distance With 14mm PCB Coil

Feature Description (continued)

7.3.2 Measuring Rp with LDC1041

The LDC1041 supports a wide range of LC combinations, with oscillation frequencies ranging from 5kHz to 5MHz and Rp ranging from 798Ω to 3.93MΩ. This range of Rp can be viewed as the maximum input range of an ADC. As illustrated in Figure 9, the range of Rp is typically much smaller than the maximum input range supported by the LDC1041. To get better resolution in the desired sensing range, the LDC1041 offers a programmable input range through the Rp_MIN and Rp_MAX registers. Refer to Calculation of Rp_MIN and Rp_MAX below for how to set these registers.

When the sensor's resonance impedance Rp drops below the programmed Rp_MIN, the LDC's Rp output will clip at its full scale output. This situation could, for example, happen when a target comes too close to the coil.

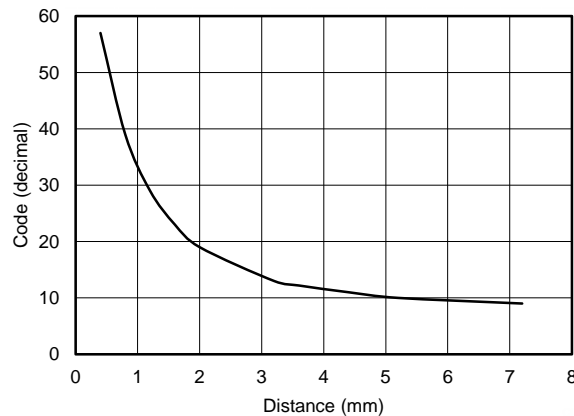


Figure 10. Transfer Characteristics Of LDC1041 With Rp_MIN= 1.347 kΩ And Rp_MAX= 38.785 kΩ

The resonance impedance can be calculated from the digital output code as follows:

$$R_p = \frac{R_{p_MAX} \times R_{p_MIN}}{R_{p_MIN} \times (1 - Y) + R_{p_MAX} \times Y}$$

Where:

- $Y = \text{Proximity Data} / 2^7$
- Rp_MAX and Rp_MIN are the maximum and minimum Rp values selected in the respective registers
- Proximity data is the LDC output, register address 0x22. (2)

Example: If Proximity data (address 0x22) is 50, Rp_MIN is 2.394 kΩ, and Rp_MAX is 38.785 kΩ, the resonance impedance is given by:

$$Y = 50 / 2^7 = 0.3906$$

$$R_p = (38785 \times 2394) / (2394 \times (1 - 0.3906) + 38785 \times 0.3906) = (92851290) / (15149.421 + 1458.9036)$$

$$R_p = 5.59 \text{ k}\Omega$$

7.3.3 Measuring Inductance with LDC1041

LDC1041 measures the sensor's frequency of oscillation using a frequency counter. The frequency counter timing is set by an external clock applied on TBCLK terminal. The sensor frequency can be calculated from the frequency counter register value (see registers 0x23 through 0x25) as follows:

$$\text{Sensor frequency, } f_{\text{sensor}} = \frac{1}{3} \times \frac{F_{\text{ext}}}{F_{\text{count}}} \times \text{Response time}$$

where

- F_ext is the frequency of the external clock
- F_count is the value obtained from the Frequency Counter Data register (address 0x23, 0x24, 0x25)
- Response Time is the programmed response time (see LDC configuration register, address 0x04) (3)

Feature Description (continued)

The sensor inductance can be determined by:

$$L = \frac{1}{C \times (2\pi \times f_{\text{sensor}})^2}$$

where

- C is the parallel capacitance of the resonator (4)

Example: If $f_{\text{ext}}=6\text{MHz}$, Response time=6144, $C=100\text{pF}$ and measured $F_{\text{count}}= 3000$ (dec) (address 0x23 through 0x25)

$$f_{\text{sensor}}=(1/3)*(6000000/3000)*(6144)= 4.096\text{MHz}$$

Now using,
$$L = \frac{1}{C \times (2\pi \times f_{\text{sensor}})^2}$$

Inductance, $L = 15.098 \mu\text{H}$

The accuracy of measurement largely depends upon the choice of the external time-base clock (TBCLK). A higher frequency will provide better measurement accuracy.

7.4 Device Functional Modes

7.4.1 Power Modes

The LDC1041 has two power modes:

1. Active Mode : In this mode the Proximity data and frequency data conversion is enabled.
2. Stand-by Mode: This is the default mode on device power-up. In this mode conversion is disabled.

7.4.2 INTB Pin Modes

The INTB terminal is a configurable output terminal which can be used to drive an interrupt on an MCU. The LDC1041 provides three different modes on INTB terminal:

1. Comparator Mode
2. Wake-Up Mode
3. DRDY Mode

LDC1041 has built-in High and Low trigger threshold registers which can be used as a comparator with programmable hysteresis or in a special mode which can be used to wake-up an MCU. These modes are explained in detail below.

7.4.2.1 Comparator Mode

In the Comparator mode, the INTB terminal is asserted or deasserted when the proximity register value increases above Threshold High or decreases below Threshold Low registers respectively. In this mode, the LDC1041 essentially behaves as a proximity switch with programmable hysteresis.

Device Functional Modes (continued)

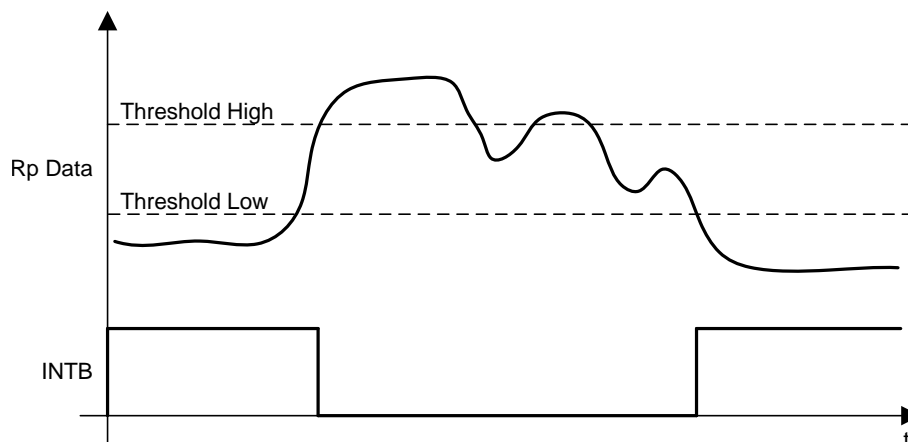


Figure 11. Behavior Of INTB Terminal In Comparator Mode

7.4.2.2 Wake-Up Mode

In Wake-Up mode, the INTB terminal is asserted when proximity register value increases above Threshold High and de-asserted when wake-up mode is disabled in INTB terminal mode register.

This mode can be used to wake-up an MCU from sleep, to conserve power.

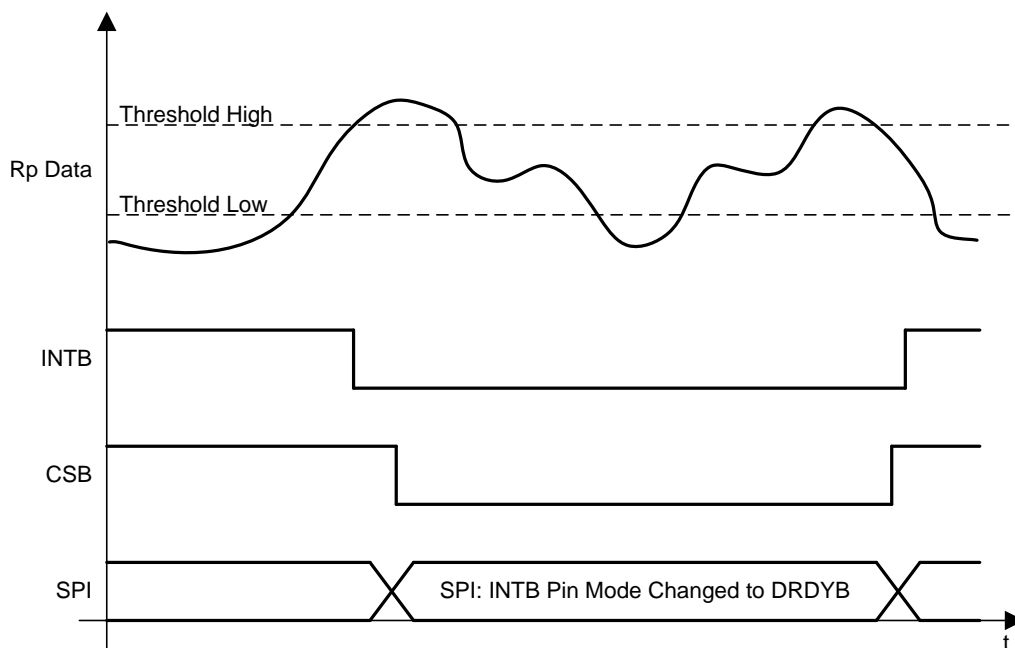


Figure 12. Behavior Of INTB Terminal In Wake-Up Mode

7.4.2.3 DRDYB Mode

In DRDY(Data Ready) mode, the INTB terminal is asserted every time the conversion data is available and de-asserted once the read command on register 0x22 is registered internally; if the read is in progress, the terminal is pulsed instead. The valid condition for new data availability is CSB high and DRDYB falling edge.

Device Functional Modes (continued)

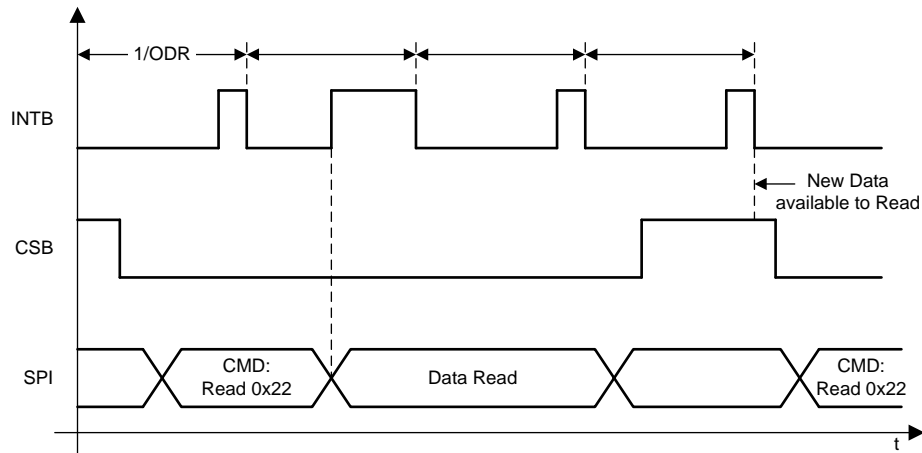


Figure 13. Behavior of INTB Terminal in DRDYB Mode with SPI Extending Beyond Subsequent Conversions

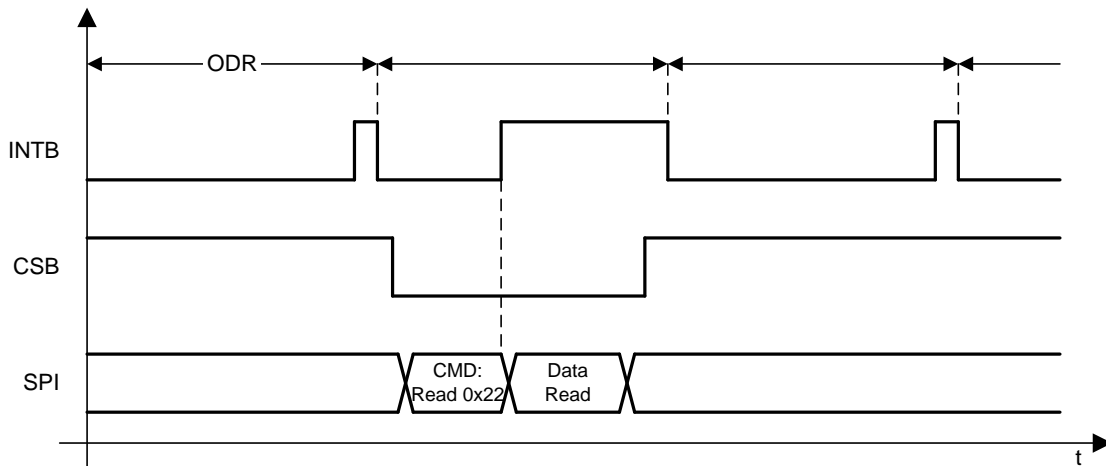


Figure 14. Behavior Of INTB Terminal In DRDYB Mode with SPI Reading The Data Within Subsequent Conversion

7.5 Programming

The LDC1041 utilizes a 4-wire SPI to access control and data registers. The LDC1041 is an SPI slave device and does not initiate any transactions.

7.5.1 SPI Description

A typical serial interface transaction begins with an 8-bit instruction, which is comprised of a read/write bit (MSB, R=1) and a 7-bit address of the register, followed by a data field which is typically 8 bits. However, the data field can be extended to a multiple of 8 bits by providing sufficient SPI clocks. Refer to the [Extended SPI Transactions](#) section below.

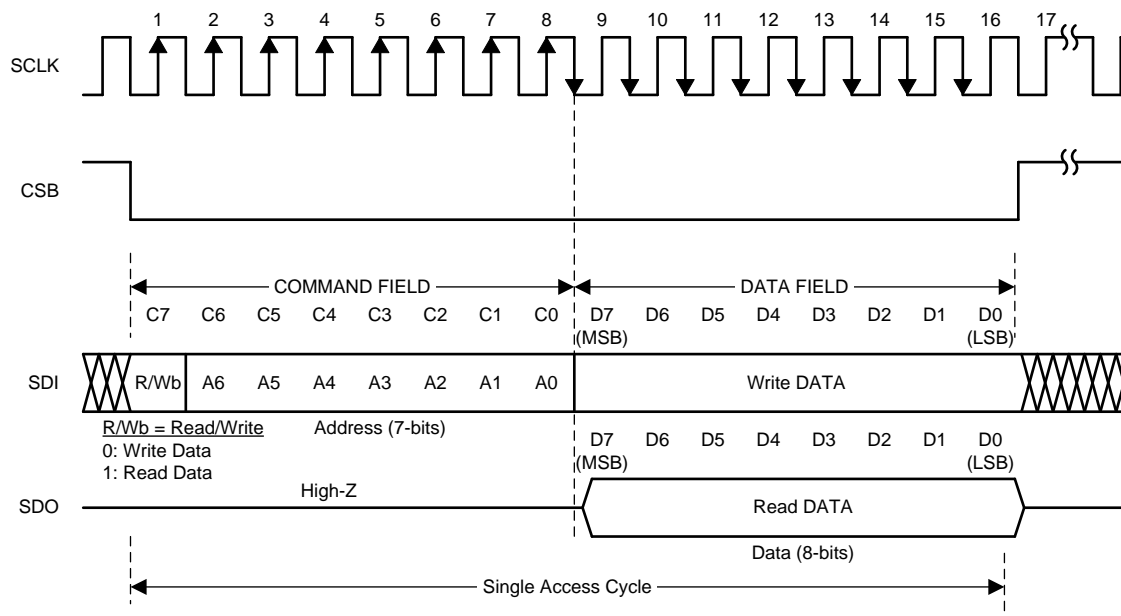


Figure 15. Serial Interface Protocol

Each assertion of CSB starts a new register access. The R/Wb bit in the command field configures the direction of the access; a value of 0 indicates a write operation and a value of 1 indicates a read operation. All output data is driven on the falling edge of the serial clock (SCLK), and all input data is sampled on the rising edge of the serial clock (SCLK). Data is written into the register on the rising edge of the 16th clock. It is required to deassert CSB after the 16th clock; if CSB is deasserted before the 16th clock, no data write will occur.

7.5.1.1 Extended SPI Transactions

A transaction may be extended to multiple registers by keeping the CSB asserted beyond the initial 16 clocks. In this mode, the register addresses increment automatically. CSB must be asserted during $8 \times (1+N)$ clock cycles of SCLK, where N is the amount of bytes to write or read during the transaction.

During an extended read access, SDO outputs the register contents every 8 clock cycles after the initial 8 clocks of the command field. During an extended write access, the data is written to the registers every 8 clock cycles after the initial 8 clocks of the command field.

Extended transactions can be used to read 8-bits of Proximity data and 24-bits of frequency data in a single SPI transaction by initiating a read from the register 0x22.

7.6 Register Map and Description

Table 1. Register Map⁽¹⁾⁽²⁾⁽³⁾

| Register Name | Address | Direction | Default | Bit 7 | Bit 6 | Bit 5 | Bit 4 | Bit 3 | Bit 2 | Bit 1 | Bit 0 |
|---------------------------------|---------|-----------|---------|----------------------|-------|---------|------------|-------------|---------------|-------|----------|
| Device ID | 0x00 | RO | 0x84 | Device ID | | | | | | | |
| Rp_MAX | 0x01 | R/W | 0x0E | Rp Maximum | | | | | | | |
| Rp_MIN | 0x02 | R/W | 0x14 | Rp Minimum | | | | | | | |
| Watchdog Timer Frequency | 0x03 | R/W | 0x45 | Min Sensor Frequency | | | | | | | |
| LDC Configuration | 0x04 | R/W | 0x1B | Reserved(000) | | | Amplitude | | Response Time | | |
| Reserved | 0x05 | RO | 0x01 | Reserved(00000001) | | | | | | | |
| Reserved | 0x06 | R/W | 0xFF | Reserved | | | | | | | |
| Comparator Threshold High MSB | 0x07 | R/W | 0xFF | Threshold High MSB | | | | | | | |
| Reserved | 0x08 | R/W | 0x00 | Reserved | | | | | | | |
| Comparator Threshold Low MSB | 0x09 | R/W | 0x00 | Threshold Low MSB | | | | | | | |
| INTB Terminal Configuration | 0x0A | R/W | 0x00 | Reserved(00000) | | | | | INTB_MODE | | |
| Power Configuration | 0x0B | R/W | 0x00 | Reserved(0000000) | | | | | | | PWR_MODE |
| Status | 0x20 | RO | | OSC Dead | DRDYB | Wake-up | Comparator | Do Not Care | | | |
| Reserved | 0x21 | RO | | Reserved(00000000) | | | | | | | |
| Proximity Data | 0x22 | RO | | Proximity Data | | | | | | | |
| Frequency Counter Data LSB | 0x23 | RO | | FCOUNT LSB | | | | | | | |
| Frequency Counter Data Mid-Byte | 0x24 | RO | | FCOUNT Mid Byte | | | | | | | |
| Frequency Counter Data MSB | 0x25 | RO | | FCOUNT MSB | | | | | | | |

(1) Values of register fields which are unused should be set to default values only.

(2) Registers 0x01 through 0x05 are Read Only when the part is awake (PWR_MODE bit is SET)

(3) R/W: Read/Write. RO: Read Only. WO: Write Only.

Table 2. Revision ID

| Address = 0x00, Default=0x84, Direction=RO | | |
|--|-------------|-------------------------|
| Bit Field | Field Name | Description |
| 7:0 | Revision ID | Revision ID of Silicon. |

Table 3. Rp_MAX

| Address = 0x01, Default=0x0E, Direction=R/W | | |
|---|------------|---|
| Bit Field | Field Name | Description |
| 7:0 | Rp Maximum | Maximum Rp that LDC1041 needs to measure. Configures the input dynamic range of LDC1041. See Table 4 for register settings. |

Table 4. Register Settings for Rp_MAX

| Register setting | Rp (kΩ) |
|------------------|----------|
| 0x00 | 3926.991 |
| 0x01 | 3141.593 |
| 0x02 | 2243.995 |
| 0x03 | 1745.329 |
| 0x04 | 1308.997 |
| 0x05 | 981.748 |
| 0x06 | 747.998 |
| 0x07 | 581.776 |
| 0x08 | 436.332 |
| 0x09 | 349.066 |
| 0x0A | 249.333 |
| 0x0B | 193.926 |
| 0x0C | 145.444 |
| 0x0D | 109.083 |
| 0x0E | 83.111 |
| 0x0F | 64.642 |
| 0x10 | 48.481 |
| 0x11 | 38.785 |
| 0x12 | 27.704 |
| 0x13 | 21.547 |
| 0x14 | 16.160 |
| 0x15 | 12.120 |
| 0x16 | 9.235 |
| 0x17 | 7.182 |
| 0x18 | 5.387 |
| 0x19 | 4.309 |
| 0x1A | 3.078 |
| 0x1B | 2.394 |
| 0x1C | 1.796 |
| 0x1D | 1.347 |
| 0x1E | 1.026 |
| 0x1F | 0.798 |

Table 5. Rp_MIN

| Address = 0x02, Default=0x14, Direction=R/W | | |
|---|------------|--|
| Bit Field | Field Name | Description |
| 7:0 | Rp Minimum | Minimum Rp that LDC1041 needs to measure. Configures the input dynamic range of LDC1041. See Table 6 for register settings. ⁽¹⁾ |

(1) This Register needs a mandatory write as it defaults to 0x14.

Table 6. Register Settings for Rp_MIN

| Register setting | Rp (kΩ) |
|------------------|----------|
| 0x20 | 3926.991 |
| 0x21 | 3141.593 |
| 0x22 | 2243.995 |
| 0x23 | 1745.329 |
| 0x24 | 1308.997 |
| 0x25 | 981.748 |
| 0x26 | 747.998 |
| 0x27 | 581.776 |
| 0x28 | 436.332 |
| 0x29 | 349.066 |
| 0x2A | 249.333 |
| 0x2B | 193.926 |
| 0x2C | 145.444 |
| 0x2D | 109.083 |
| 0x2E | 83.111 |
| 0x2F | 64.642 |
| 0x30 | 48.481 |
| 0x31 | 38.785 |
| 0x32 | 27.704 |
| 0x33 | 21.547 |
| 0x34 | 16.160 |
| 0x35 | 12.120 |
| 0x36 | 9.235 |
| 0x37 | 7.182 |
| 0x38 | 5.387 |
| 0x39 | 4.309 |
| 0x3A | 3.078 |
| 0x3B | 2.394 |
| 0x3C | 1.796 |
| 0x3D | 1.347 |
| 0x3E | 1.026 |
| 0x3F | 0.798 |

Table 7. Watchdog Timer Frequency

| Address = 0x03, Default=0x45, Direction=R/W | | |
|---|----------------------|---|
| Bit Field | Field Name | Description |
| 7:0 | Min Sensor Frequency | <p>Sets the watchdog timer. The Watchdog timer is set based on the lowest sensor frequency.</p> $N = 68.94 \times \log_{10} \left(\frac{F}{2500} \right)$ <p>where</p> <ul style="list-style-type: none"> F is the sensor frequency <p>(5)</p> <p>Example: If Sensor frequency is 1Mhz Min Sensor Frequency = $68.94 \times \log_{10}(1M/2500)$ = Round to nearest integer(179.38) = 179</p> |

Table 8. LDC Configuration

| Address = 0x04, Default=0x1B, Direction=R/W | | |
|---|---------------|--|
| Bit Field | Field Name | Description |
| 7:5 | Reserved | Reserved to 0 |
| 4:3 | Amplitude | Sets the oscillation amplitude 00:1V 01:2V 10:4V 11:Reserved |
| 2:0 | Response Time | 000: Reserved 001: Reserved 010: 192 011: 384 100: 768 101: 1536 110: 3072 111: 6144 |

Table 9. Comparator Threshold High MSB

| Address = 0x07, Default=0xFF, Direction=R/W | | |
|---|----------------|--------------------------|
| Bit Field | Field Name | Description |
| 7:0 | Threshold High | Threshold High Register. |

Table 10. Comparator Threshold Low MSB

| Address = 0x09, Default=0x00, Direction=R/W | | |
|---|---------------|-------------------------|
| Bit Field | Field Name | Description |
| 7:0 | Threshold Low | Threshold Low Register. |

Table 11. INTB Terminal Configuration

| Address = 0x0A, Default=0x00, Direction=R/W | | |
|---|------------|---|
| Bit Field | Field Name | Description |
| 7:3 | Reserved | Reserved to 0 |
| 2:0 | Mode | 000: All modes disabled 001: Wake-up Enabled on INTB terminal 010: INTB terminal indicates the status of Comparator output 100: DRDYB Enabled on INTB terminal All other combinations are Reserved |

Table 12. Power Configuration

| Address = 0x0B, Default=0x00, Direction=R/W | | |
|---|------------|--|
| Bit Field | Field Name | Description |
| 7:1 | Reserved | Reserved to 0 |
| 0 | PWR_MODE | 0:Stand-By mode 1:Active Mode. Conversion is Enabled Refer to Power Modes for more details. |

Table 13. Status

| Address = 0x20, Default=NA, Direction=RO | | |
|--|-------------|---|
| Bit Field | Field Name | Description |
| 7 | OSC status | 1:Indicates oscillator overloaded and stopped 0:Oscillator working |
| 6 | Data Ready | 1:No new data available 0:Data is ready to be read |
| 5 | Wake-up | 1:Wake-up disabled 0:Wake-up triggered. Proximity data is more than Threshold High value. |
| 4 | Comparator | 1:Proximity data is less than Threshold Low value 0:Proximity data is more than Threshold High value |
| 3:0 | Do not Care | |

Table 14. Proximity Data

| Address = 0x22, Default=NA, Direction=RO | | |
|--|----------------|----------------|
| Bit Field | Field Name | Description |
| 7:0 | Proximity data | Proximity data |

Table 15. Frequency Counter LSB

| Address = 0x23, Default=NA, Direction=RO | | |
|--|--------------------------|--|
| Bit Field | Field Name | Description |
| 7:0 | FCOUNT LSB (FCOUNT[7:0]) | LSB of Frequency Counter. Sensor frequency can be calculated using the output data rate. Please refer to the Measuring Inductance with LDC1041 . |

Table 16. Frequency Counter Mid-Byte

| Address = 0x24, Default=NA, Direction=RO | | |
|--|--------------------------------|---------------------------------|
| Bit Field | Field Name | Description |
| 7:0 | FCOUNT Mid byte (FCOUNT[15:8]) | Middle Byte of Output data rate |

Table 17. Frequency Counter MSB

| Address = 0x25, Default=NA, Direction=RO | | |
|--|----------------------------|-------------------------|
| Bit Field | Field Name | Description |
| 7:0 | FCOUNT MSB (FCOUNT[23:16]) | MSB of Output data rate |

Conversion data is updated to these registers only when a read is initiated on 0x22 register. If the read is delayed between subsequent conversions, these registers are not updated until another read is initiated on 0x22.

8 Applications and Implementation

8.1 Application Information

8.1.1 Calculation of Rp_MIN and Rp_MAX

Different sensing applications may have a different range of the resonance impedance Rp to measure. The LDC1041 measurement range of Rp is controlled by setting 2 registers – Rp_MIN and Rp_MAX. For a given application, Rp must never be outside the range set by these register values, otherwise the measured value will be clipped. For optimal sensor resolution, the range of Rp_MIN to Rp_MAX should not be unnecessarily large. The following procedure is recommended to determine the Rp_MIN and Rp_MAX register values.

8.1.1.1 Setting Rp_MAX

Rp_MAX sets the upper limit of the LDC1041 resonant impedance input range.

- Configure the sensor such that the eddy current losses are minimized. As an example, for a proximity sensing application, set the distance between the sensor and the target to the maximum sensing distance.
- Measure the resonant impedance Rp using an impedance analyzer.
- Multiply Rp by 2 and use the next higher value from [Table 4](#).

Note that setting Rp_MAX to a value not listed in [Table 4](#) can result in indeterminate behavior.

8.1.1.2 Setting Rp_MIN

Rp_MIN sets the lower limit of the LDC1041 resonant impedance input range.

- Configure the sensor such that the eddy current losses are maximized. As an example, for a proximity sensing application, set the distance between the sensor and the metal target to the minimum sensing distance.
- Measure the resonant impedance Rp using an impedance analyzer.
- Divide the Rp value by 2 and then select the next lower Rp value from [Table 6](#).

Note that setting Rp_MIN to a value not listed on [Table 6](#) can result in indeterminate behavior. In addition, Rp_MIN powers on with a default value of 0x14 which must be set to a value from [Table 6](#) prior to powering on the LDC.

8.1.2 Output Data Rate

Output data rate of LDC1041 depends on the sensor frequency, f_{sensor} and 'Response Time' field in LDC Configuration register(Address:0x04).

$$\text{Output Data Rate} = \frac{f_{\text{sensor}}}{\left(\frac{\text{Response time}}{3}\right)} \quad (6)$$

8.1.3 Choosing Filter Capacitor (CFA and CFB Terminals)

The Filter capacitor is critical to the operation of the LDC1041. The capacitor should be low leakage, temperature stable, and it must not generate any piezoelectric noise (the dielectrics of many capacitors exhibit piezoelectric characteristics and any such noise is coupled directly through Rp into the converter). The optimal capacitance values range from 20pF to 100nF. The value of the capacitor is based on the time constant and resonating frequency of the LC tank.

If a ceramic capacitor is used, then a C0G (or NP0) grade dielectric is recommended; the voltage rating should be $\geq 10\text{V}$. The traces connecting CFA and CFB to the capacitor should be as short as possible to minimize any parasitics.

For optimal performance, the chosen filter capacitor, connected between terminals CFA and CFB, needs to be as small as possible, but large enough such that the active filter does not saturate. The size of this capacitor depends on the time constant of the sense coil, which is given by L/R_s , (L =inductance, R_s =series resistance of the inductor at oscillation frequency). The larger this time constant, the larger filter capacitor is required. Hence, this time constant reaches its maximum when there is no target present in front of the sensing coil.

Application Information (continued)

The following procedure can be used to find the optimal filter capacitance:

1. Start with a large filter capacitor. For a ferrite core coil, 10nF is usually large enough. For an air coil or PCB coil, 100pF is usually large enough.
2. Power on the LDC and set the desired register values. Minimize the eddy currents losses. This is done by minimizing the amount of conductive target covering the sensor. For an axial sensing application, the target should be at farthest distance from coil. For a lateral or angular position application, the target coverage of the coil should be minimized.
3. Observe the signal on the CFB terminal using a scope. Since this node is very sensitive to capacitive loading, it is recommended to use an active probe. As an alternative, a passive probe with a 1kΩ series resistance between the tip and the CFB terminal can be used.
4. Vary the values of the filter capacitor until that the signal observed on the CFB terminal has an amplitude of approximate 1V peak-to-peak. This signal scales linearly with the reciprocal of the filter capacitance. For example, if a 100pF filter capacitor is applied and the signal observed on the CFB terminal has a peak-to-peak value of 200mV, the desired 1V peak-to-peak value is obtained using a $200\text{mV} / 1\text{V} * 100\text{pF} = 20\text{pF}$ filter capacitor.

8.2 Typical Applications

8.2.1 Axial Distance Sensing Using a PCB Sensor with LDC1041

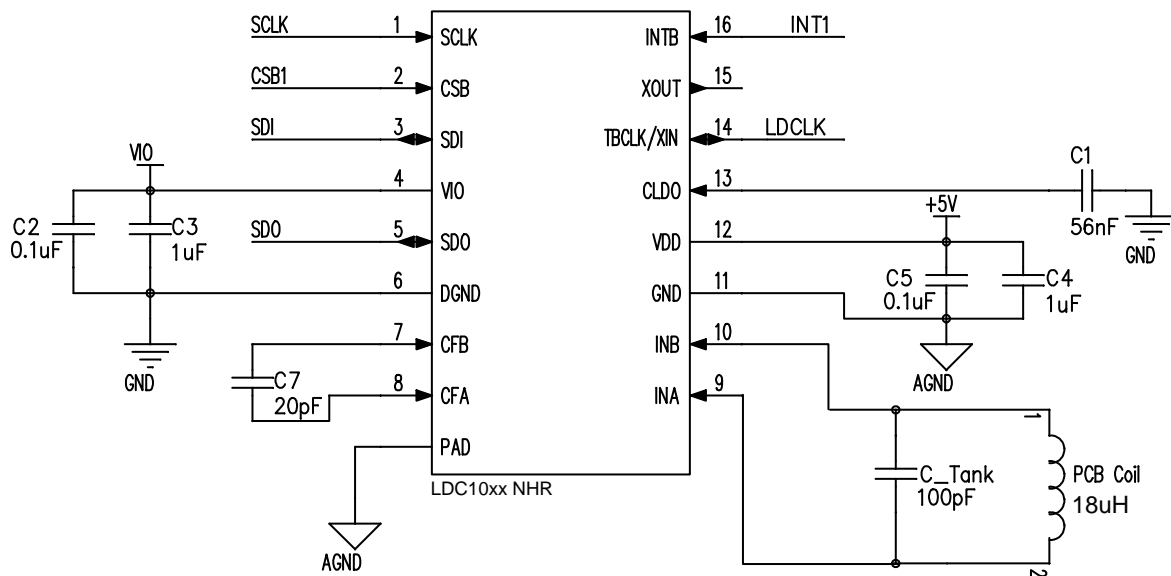


Figure 16. Typical Application Schematic, LDC10xx

8.2.1.1 Design Requirements

For this design example, use the following as the input parameters.

Table 18. Design Parameters

| DESIGN PARAMETER | EXAMPLE VALUE |
|---------------------------------|---|
| Minimum sensing distance | 1 mm |
| Maximum sensing distance | 8 mm |
| Output data rate | 78 KSPS (Max data rate with LDC10xx series) |
| Number of PCB layers for sensor | 2 layers |

8.2.1.2 Detailed Design Procedure

8.2.1.2.1 Sensor and Target

In this example, consider a sensor with the below characteristics.

Table 19. Sensor Characteristics

| PARAMETER | VALUE |
|---------------------|----------|
| Layers | 2 |
| Thickness of copper | 1 Oz |
| Coil shape | Circular |
| Number of turns | 23 |
| Trace thickness | 4 mil |
| Trace spacing | 4 mil |
| PCB core material | FR4 |
| Rp @ 1 mm | 5 kΩ |
| Rp @ 8 mm | 12.5 kΩ |
| Nominal Inductance | 18 μH |

Target material used is stainless steel

8.2.1.2.2 Calculating Sensor Capacitor

Sensor frequency depends on various factors in the application. In this example since one of the design parameter is to achieve output data rate of 78 KSPS, sensor frequency can be calculated as below.

$$\text{Output Data Rate} = \frac{f_{\text{sensor}}}{\left(\frac{\text{Response time}}{3}\right)} \tag{7}$$

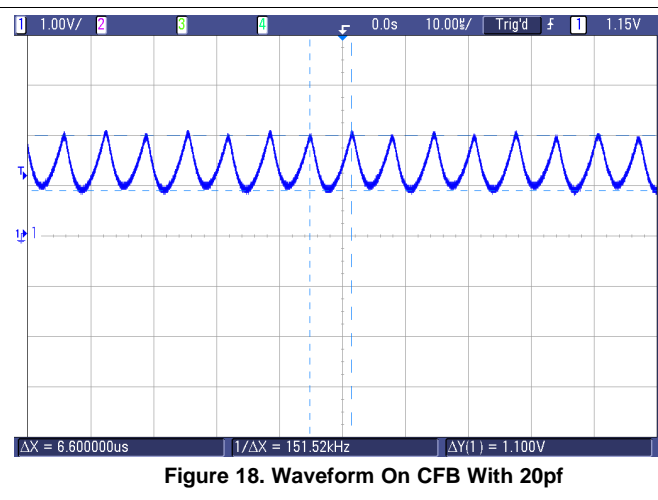
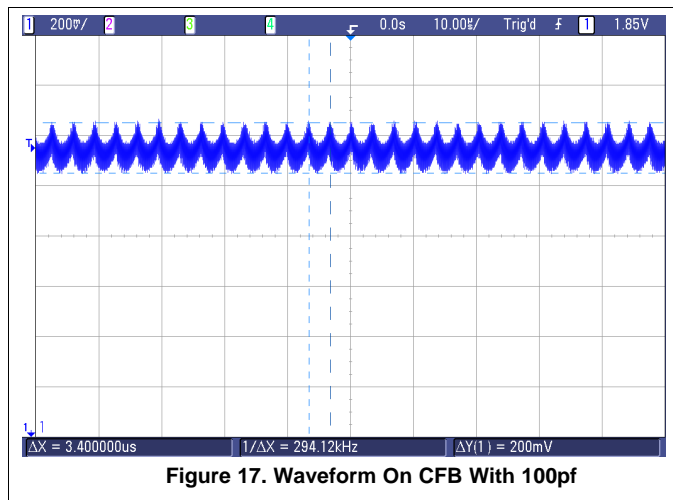
With the lowest Response time of 192 and output data rate of 78 KSPS, sensor frequency calculated using the above formula is 4.99 MHz.

Now, using the below formula sensor capacitor is calculated to be 55 pF with a sensor inductance of 18 μH

$$L = \frac{1}{C \times (2\pi \times f_{\text{sensor}})^2} \tag{8}$$

8.2.1.2.3 Choosing Filter Capacitor

Using the steps given in [Choosing Filter Capacitor \(CFA and CFB Terminals\)](#) filter capacitor for the example sensor is 20 pF. Below waveform shows the pattern on CFB pin with 100 pF and 20 pF filter capacitor.



8.2.1.2.4 Setting Rp_MIN and Rp_MAX

Calculating value for Rp_MAX Register : Rp at 8mm is 12.5kΩ, 12500×2 = 25000. In [Table 4](#), then 27.704 kΩ is the nearest value larger than 25kΩ; this corresponds to Rp_MAX value of 0x12

Calculating value for Rp_MIN Register : Rp at 1mm is 5kΩ, 5000/2 = 2500. In [Table 6](#), 2.394kΩ is the nearest value lower than 2.5kΩ; this corresponds to Rp_MIN value of 0x3B

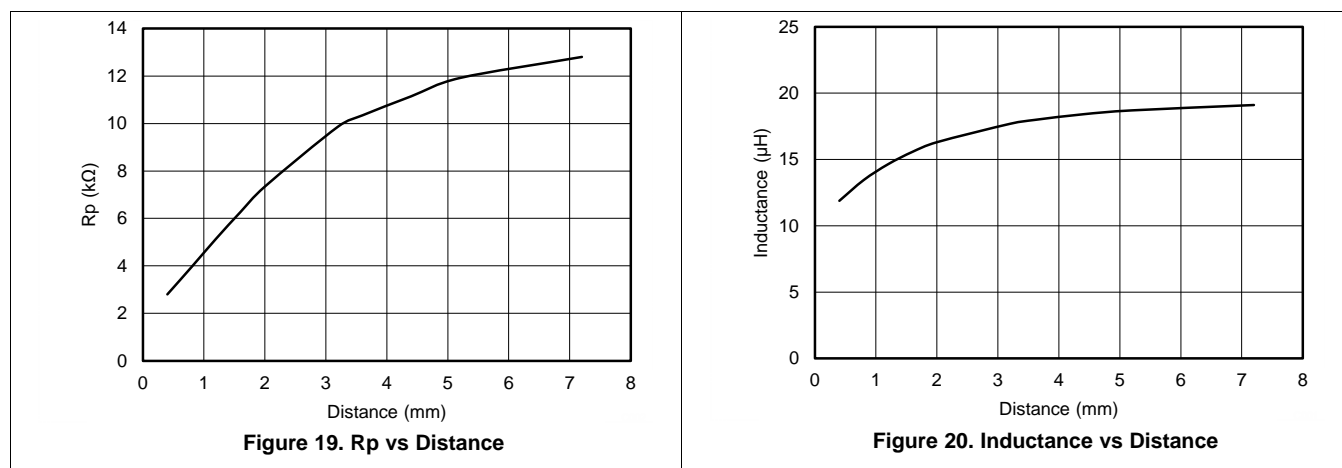
8.2.1.2.5 Calculating Minimum Sensor Frequency

Using,

$$N = 68.94 \times \log_{10} \left(\frac{F}{2500} \right) \quad (9)$$

N is 227.51, round off to 228 decimal. This value has to be written into Watchdog Timer Register, which is used to wake up the internal circuit when the sensor is saturated.

8.2.1.3 Application Curves



8.2.2 Linear Position Sensing Application Diagram

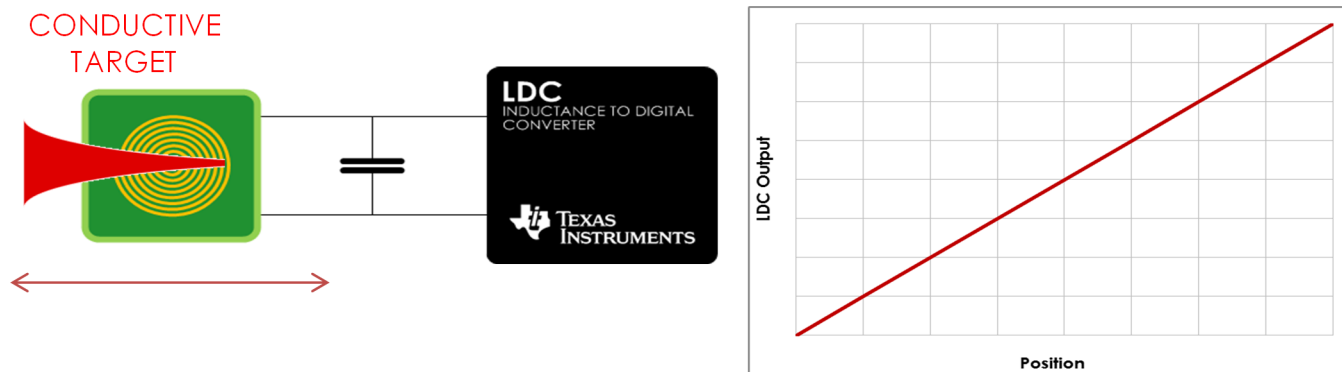


Figure 21. Linear Position Sensing

8.2.3 Angular Position Sensing Application Diagram

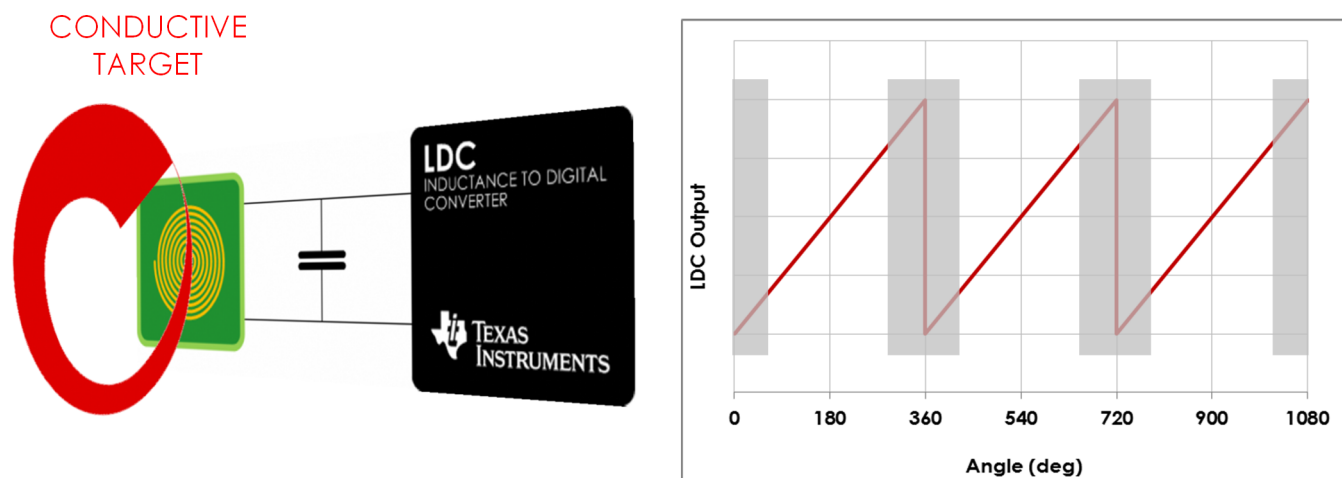


Figure 22. Angular Position Sensing

9 Power Supply Recommendations

The LDC1041 is designed to operate from an analog supply range of 4.75 V to 5.25 V and digital I/O supply range of 1.8V to 5.25V. The analog supply voltage should be greater than or equal to the digital supply voltage for proper operation of the device. The supply voltage should be well regulated. If the supply is located more than a few inches from the LDC1041 additional bulk capacitance may be required in addition to the ceramic bypass capacitors. An electrolytic capacitor with a value of 10uF is a typical choice.

10 Layout

10.1 Layout Guidelines

- The VDD and VIO terminal should be bypassed to ground with a low ESR ceramic bypass capacitor. The typical recommended bypass capacitance is 0.1uF ceramic with a X5R or X7R dielectric.
- The optimum placement is closest to the VDD/VIO and GND/DGND terminals of the device. Care should be taken to minimize the loop area formed by the bypass capacitor connection, the VDD/VIO terminal, and the GND/DGND terminal of the IC. See [Figure 23](#) for a PCB layout example.
- The CLDO terminal should be bypassed to digital ground (DGND) with a 56nF ceramic bypass capacitor.
- The filter capacitor selected for the application using the procedure described in section [Choosing Filter Capacitor \(CFA and CFB Terminals\)](#) is connected between CFA and CFB terminals. Place the filter capacitor close to the CFA and CFB terminals. Do not use any ground/power plane below the capacitor and the trace connecting the capacitor and the CFA /CFB terminals.
- Use of two separate ground plane for GND and DGND is recommended with a start connection. See [Figure 23](#) for a PCB layout example.

10.2 Layout Example

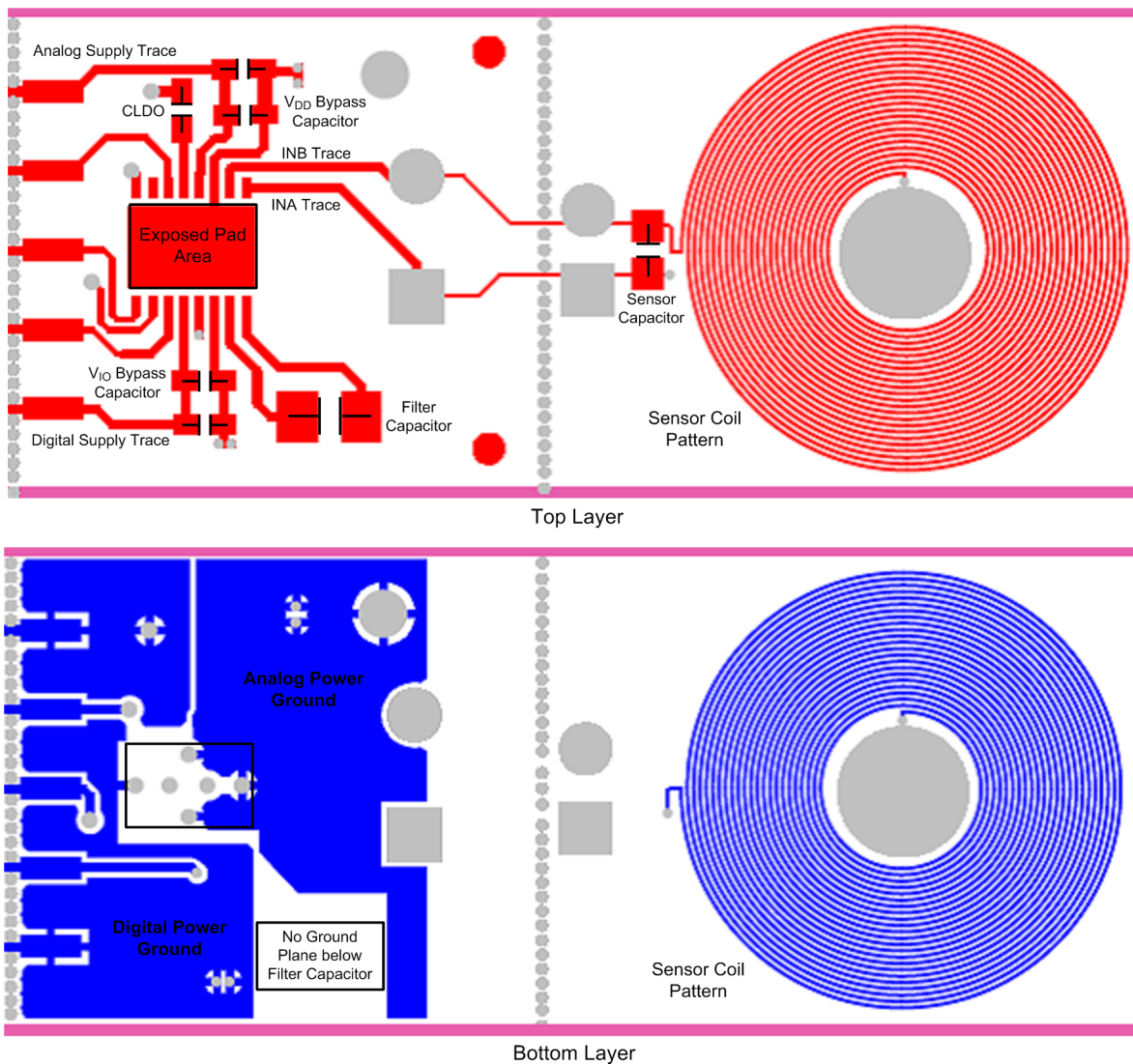


Figure 23. LDC10xx Board Layout

11 Device and Documentation Support

11.1 Trademarks

All trademarks are the property of their respective owners.

11.2 Electrostatic Discharge Caution



These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

11.3 Glossary

[SLYZ022](#) — *TI Glossary*.

This glossary lists and explains terms, acronyms and definitions.

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical packaging and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

PACKAGING INFORMATION

| Orderable Device | Status (1) | Package Type | Package Drawing | Pins | Package Qty | Eco Plan (2) | Lead/Ball Finish (6) | MSL Peak Temp (3) | Op Temp (°C) | Device Marking (4/5) | Samples |
|------------------|---------------|--------------|-----------------|------|-------------|-------------------------|-------------------------|----------------------|--------------|-------------------------|-------------------------|
| LDC1041NHRJ | ACTIVE | WSON | NHR | 16 | 4500 | Green (RoHS & no Sb/Br) | CU SN | Level-1-260C-UNLIM | -40 to 125 | LDC1041 | Samples |
| LDC1041NHRR | ACTIVE | WSON | NHR | 16 | 1000 | Green (RoHS & no Sb/Br) | CU SN | Level-1-260C-UNLIM | -40 to 125 | LDC1041 | Samples |
| LDC1041NHRT | ACTIVE | WSON | NHR | 16 | 250 | Green (RoHS & no Sb/Br) | CU SN | Level-1-260C-UNLIM | -40 to 125 | LDC1041 | Samples |

(1) The marketing status values are defined as follows:

ACTIVE: Product device recommended for new designs.

LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.

NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.

PREVIEW: Device has been announced but is not in production. Samples may or may not be available.

OBSOLETE: TI has discontinued the production of the device.

(2) Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check <http://www.ti.com/productcontent> for the latest availability information and additional product content details.

TBD: The Pb-Free/Green conversion plan has not been defined.

Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.

Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.

Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

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TAPE AND REEL INFORMATION



QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

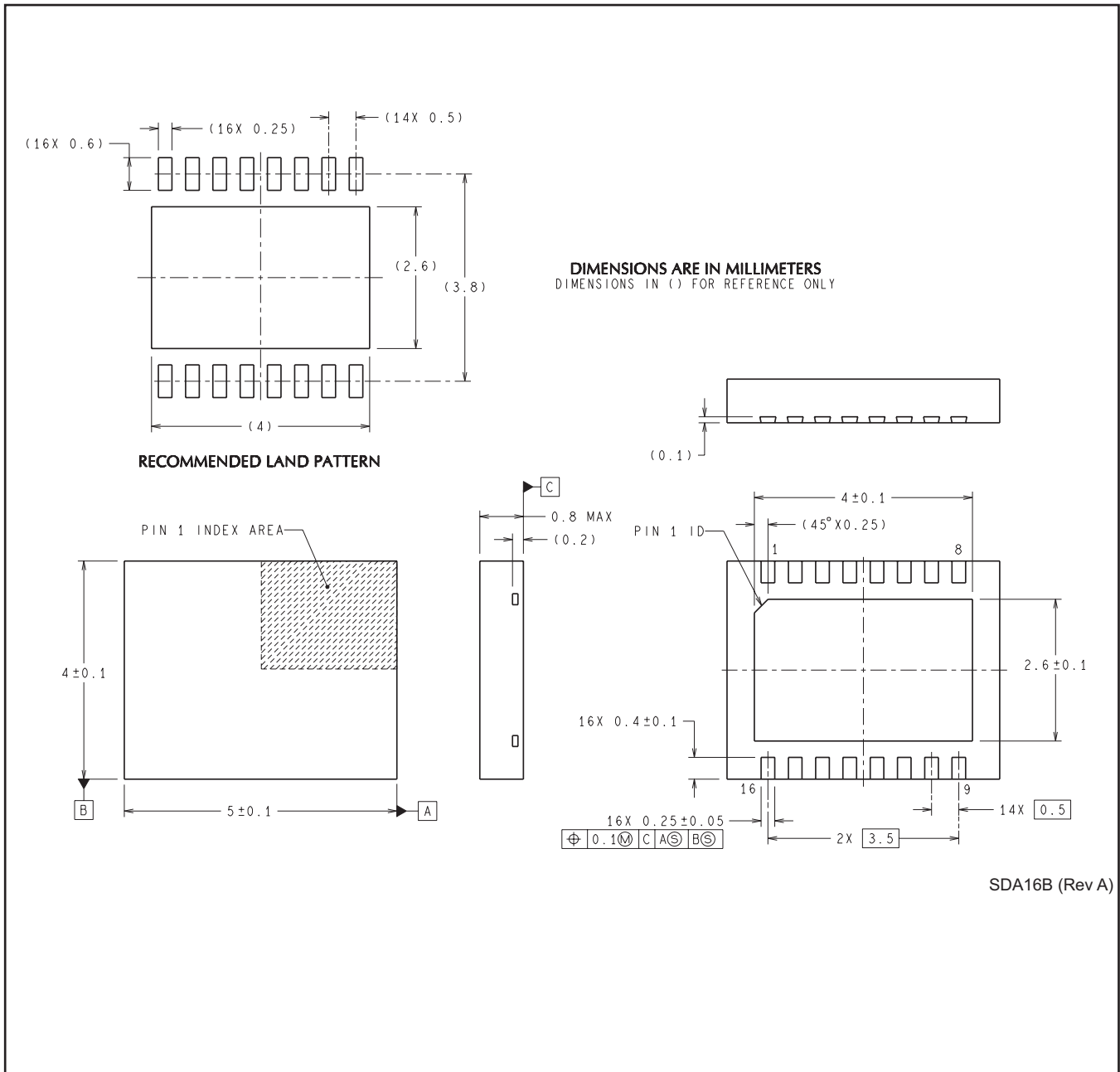
| Device | Package Type | Package Drawing | Pins | SPQ | Reel Diameter (mm) | Reel Width W1 (mm) | A0 (mm) | B0 (mm) | K0 (mm) | P1 (mm) | W (mm) | Pin1 Quadrant |
|-------------|--------------|-----------------|------|------|--------------------|--------------------|---------|---------|---------|---------|--------|---------------|
| LDC1041NHRJ | WSON | NHR | 16 | 4500 | 330.0 | 12.4 | 4.3 | 5.3 | 1.3 | 8.0 | 12.0 | Q1 |
| LDC1041NHRR | WSON | NHR | 16 | 1000 | 178.0 | 12.4 | 4.3 | 5.3 | 1.3 | 8.0 | 12.0 | Q1 |
| LDC1041NHRT | WSON | NHR | 16 | 250 | 178.0 | 12.4 | 4.3 | 5.3 | 1.3 | 8.0 | 12.0 | Q1 |

TAPE AND REEL BOX DIMENSIONS


*All dimensions are nominal

| Device | Package Type | Package Drawing | Pins | SPQ | Length (mm) | Width (mm) | Height (mm) |
|-------------|--------------|-----------------|------|------|-------------|------------|-------------|
| LDC1041NHRJ | WSON | NHR | 16 | 4500 | 367.0 | 367.0 | 35.0 |
| LDC1041NHRR | WSON | NHR | 16 | 1000 | 210.0 | 185.0 | 35.0 |
| LDC1041NHRT | WSON | NHR | 16 | 250 | 210.0 | 185.0 | 35.0 |

NHR0016B



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