Achieving Ultra-Low Power design in Always-On and Power Cycled applications with Nanopower Op Amps and Nanotimers

Systems Training

Nikhil Dua
Applications Engineer
Integrated Signal Chain, PSP

Paul Grohe
Applications Engineer
Integrated Signal Chain, PSP
Agenda

• Always-On Vs. Power Cycled definition

• TI Nanopower Amplifier solutions for Always-on applications

• How to apply amplifiers in nanopower systems
  – Gas Sensing & PIR Motion Detection
  – Design Considerations
  – Power Cycling

• Using Nano-timers when Always-On is not feasible.
  – How to apply functionality & features of nanotimers to applications.
  – Where & why we win in Duty-Cycled systems.
    • Duty cycling & pairing with TI MCUs to reduce system power consumption
    • Low Power Humidity + Temp Sensing Products for Battery-Powered Applications

• Wrap-up
  – TI Nanopower Selection tools and getting help
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### Always-On vs. Power Cycled definition

#### Always-On
(continuously measuring)

- Asynchronous, fast moving or short-term conditions or events
  - Movement, breakage, overloads & impacts
- Continuously biased sensors
  - Electrochemical cells
- Charge based sensors with a recovery time if disturbed
  - Ion chamber
- Continuously integrated-over-time sensors
  - Gas sensors, Dosimeters

#### Power Cycled
(sleep → power-up & measure → sleep)

- For slow changing conditions that can be sampled at discrete intervals
  - Temperature
  - Humidity
  - Particulates
- For circuitry that requires high power or very low noise during measurement period
  - Optical Measurements
  - Ultrasonic Measurements
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Where Low-Power Analog Products Go

Building Automation

Internet of Things (IoT)

Wearables & Personal Medical Devices

Wired and Wireless

- Battery
- ZigBee Transceiver
- LDO
- Boost

Energy harvested

- Texas Instruments
# TI NanoPower Portfolio for Always ON

<table>
<thead>
<tr>
<th>Specs</th>
<th>LPV80x</th>
<th>LPV521</th>
<th>LPV542</th>
<th>LPV81x</th>
<th>OPAx369</th>
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<td>1 &amp; 2</td>
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<td>2</td>
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<td>$I_Q$ (max)</td>
<td>415 nA</td>
<td>400 nA</td>
<td>800 nA</td>
<td>495 nA</td>
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<td>$V_{OS}$ (max)</td>
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<td>3 mV</td>
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<td>1.6V to 5.5V</td>
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<td>SC70</td>
<td>MSOP8, DFN8</td>
<td>SOT23 MSOP8</td>
<td>SC70, SOT23 MSOP8</td>
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</table>

**NEW**
Trimmed Offset

Overview

- Laser trim at wafer sort
  - Minimizes inherent transistor mismatch
- Digital trim after packaging
  - Minimizes inherent input transistor mismatch and errors induced by package stress
- Each trim method has tradeoffs with die size and power consumption

Typical Circuits that Benefit Trimmed Vos

Problems Solved

- Ultra-low offset voltage
- Lower Temperature Drift (TcVos)
- Offers new level of CMOS amplifier performance
- DigiTrim Trims out package shift

- OPAx376 LMP223x
- OPAx192 LPV81x
- OPAx727 TLV881x
  ..And many more!
Zero Crossover Inputs

Traditional Rail to Rail Input

Transition zone “glitch” about 1V below the rail

Zero Crossover Input

No “Glitch”! Smooth transition to beyond the rail

LMV951  OPAx325  OPAx365  OPAx369
**EMI Protection Built-In**

**Overview**

- External Electromagnetic interference (EMI) from RF sources (GSM, WiFi) causes a shift in the DC offset voltage.
- EMIRR (EMI Rejection Ratio) is the measure of the immunity of the op-amp to EMI.
- EMI Filters added to inputs to reduce the effect

**Implementation**

- Offset shift due to EMI
- No Offset shift due to EMI

**Problem Solved**
Radiated EMI Testing

Photo of an actual test done with the LPV802
The results are available in Application Note SNOA937
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Gas Detection Example – Design Requirements

• Goal #1:
  – Create a linear output voltage relative to changes in gas concentration

• Goal #2:
  – Cause minimum impact on performance or life of sensor with low input bias current and low input offset voltage

• Goal #3:
  – Maximize battery life in this “Always-On” application by minimizing quiescent current
Approach for 3-lead Sensors

Maintains constant, linear response to changes in gas concentration

- Low offset drift over temperature maintains accurate bias voltage
- Low bias current reduces loading errors on the sensor
Add second 2\textsuperscript{nd} Gain Stage for Scaling

Transimpedance Amplifier (I to V)  Scaling & Level-Shift Amplifier

Needs Low Offset, So choose LPV811
Approaches for 2-lead Sensors

Ground Referenced

- Simplest implementation
- Susceptible to negative “dead-band” if amplifier or sensor offset is *negative*!
- Amplifier must source sensor current!

Buffered

- Defined “zero” reference voltage above ground
- Prevents “dead-band”
- Allows for sensor offsets
- Buffer must sink sensor current
Offset Voltage and Dynamic Range

Dynamic range (total useful output swing) may be limited by:

- Low operating voltages, as low as 1.6V due to supply “droop”
- Reduced available output swing. Real-world loads may reduce available output swing
- Available output swing may be limited by ADC input range:
  - Processor based ADC maximum inputs may be limited by processor voltage (typ 3.3V)
  - Range may be further limited by ADC internal reference voltage (2.5V)
- Amplifier offset voltage may also eat into dynamic range, or, worse, cause “dead-zone”
  - Use low offset amplifier to minimize offset effects (LPV811)
  - Bias zero point above ground – may require another amplifier (LPV812)
- Large sensor offsets may eat into dynamic range
  - Countermeasures to cancel sensor offset may require extra supply current or devices
Approaches for 2-lead O2 Sensors

Low amplifier offset required because...

- High gain (>100x) multiplies amplifier offset voltage, creating error
- Ground referenced
  - Limits measurement “dead-band” if amplifier offset is negative
- Small input signal (~10mV)
- Choose LPV811 for low offset voltage to minimize error!

[Diagram of LPV811 amplifier circuit]
Design Considerations for Nanopower O2 Circuit

To fully optimize the nanopower O2 circuit, the values of the passive components must be considered.

- Feedback resistors are a load on the amplifier ($R_L = R_1 + R_2$)
  - DC quiescent current through feedback resistors can exceed the nanoamp amplifier quiescent current!
- To minimize quiescent current, large value resistors are required
  - $10k\Omega = 100\mu A\text{ per volt}$
  - $100k\Omega = 10\mu A\text{ per volt}$
  - $10M\Omega = 100nA\text{ per volt}$
- Large resistance values means higher thermal (“Johnson”) noise!
  - $10 k\Omega = 12.8nV\sqrt{Hz}$
  - $1 M\Omega = 128nV\sqrt{Hz}$
- The wider the signal bandwidth – the higher the overall (peak to peak) noise
  - Noise increases with the square root of the signal bandwidth
    - $10 k\Omega$ noise over a 10Hz BW = $12.8nV * \sqrt{10} * 6 = 243\text{ nVp-p}$
    - $10 M\Omega$ noise over 10Hz BW = $405nV * \sqrt{10} * 6 = 7.67\mu Vp-p$
  - Increase C2 to create a low-pass filter to reduce noise
TI Designs – Proven Performance

**TIDA – 00756**: Low Power CO Gas Sensor w/ BLE Connectivity
- Use of Nano-Power Analog for Ultra-Low Power Design Life from single CR2032 Coin Cell
- Low Standby Current (CO sensor remains active)
- BLE Communication w/ CC2650
- Self test for the sensor

**TIDA – 00854**: Micropower Electrochemical Gas Sensor Amplifier

Micropower Potentiostat Circuit for 3 Terminal Electrochemical and Gas Sensors utilizing a LaunchPad board.
Examples

Always On: Motion Detection with PIR
Always On: Motion Sense with PIR Sensor for IoT

- Pyroelectric Sensor converts infra-red heat into voltage
- Small sensor signal output (<100uV) requires amplification
- Requires 10Hz AC signal bandwidth at gains of up to 500V/V. DC accuracy not needed
- Multi-channel devices to distribute gain in multiple stages to increase bandwidth and level shift to window comparator reference center
- Lengthen battery life with low quiescent current
  - Enables the use of smaller, cheaper batteries
  - Enables the use of energy harvesting techniques
PIR Approach

Blocks DC Gain, sets LF pole
Prevents over-charging of capacitors
Sets bias current for sensor

VDD

IR

PIR

Sensor

VSENSEOR

Stage 1 Gain, Clamp and BPF

LPV802a

VOUT1

Amplifiers (2)

LPV802b

Stage 2 Gain and BPF

VDD

PIR_HI

PIR_LO

Sets center-point of comparison window

Window Comparators (2)
Examples

Always ON: Ionization Smoke Detection
Ionization Smoke Detection

- Dual channel amplifier with <1pA current over the temperature range of 0°C to 50°C
- SOIC package preferred to minimize leakage current on input
- Maximize battery life in this always-on application by minimizing quiescent current
- New UL-217 requirement: Photoelectric (smoldering) and Ionization (fast flame) smoke detection are required…
Examples

Always On AND Duty Cycled: Smoke Detection
Some Applications use both methods!

- Two types of smoke detectors
  - Ionization (always ON) and Photoelectric (power-cycled)
- Photoelectric is power-cycled since 100+mA’s required to exercise the LED and fast-settling, low-noise photodiode amplifier draws several mA while operating

**Ionization:**
Responds faster to “fast-flame” fires, but must be operating continuously

- Ion Out
- Guard
- Sense
- REF

**Photoelectric:**
Responds much faster to smoldering fires, but requires a lot of current!

- 100+ mA's
- ~10ms light Pulses

LPV802

Fast, Low noise amplifier circuit uses mA's while operating

OPA316
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### Key Duty Cycled Applications: Why it Matters

#### IoT
- Sensor Node
- WiFi node
- Data logger

#### Building Automation
- Smoke detector
- Shock detector
- Deposit Box Detector
- Data logger

#### Automotive Accessories
- Car key
- TPMS

#### Metering
- Gas meter
- Water meter
Duty Cycled Applications: Why Nanotimer?

- In power-cycled applications, the uC or the transceiver sleeps for most of their life
- These devices have low power or sleep modes that are not very efficient
- Nanotimer devices are designed to reduce the power consumption by at least an order of magnitude vs. µC sleep modes

> 500nA

35nA
# Nanotimers vs. 555 Timers/Discrete Solutions

<table>
<thead>
<tr>
<th>Nanotimers</th>
<th>Discrete Solutions</th>
<th>555 Timers</th>
</tr>
</thead>
</table>
| • Controls μ-controller’s power when in sleep mode | • Timer with Resistor and Capacitors (RC Timer)  
  o Combine with transistors  
  o Combine with comparator | • Input to μ-controller or other device with a PWM input |
| • Greatly reduces power consumption | • Not optimized for slow speed = Higher Current Burn! | • Creates time delays or oscillation |
| • Timer Accuracy: 1% (@25°C, 2.5V, excluding R_{ext} precision) | • Accuracy: Dependent on accuracy of Resistor and Capacitor values | • Accuracy: Dependent on accuracy of Resistor and Capacitor values => Increasing Cost + Burning Current! |
| • $I_Q \leq 35$ nA | ![Diagram of RC Timer] | • $I_Q \geq 50$ μA |

![Diagram of RC Timer](image_url)
Programmable Ultra Low Power Timer with Watchdog Function

Battery ➔ TPL5010 ➔ Microcontroller

35nA Power Consumption

Microcontroller can be put in deep sleep and woken up periodically (internal oscillator switched off)

Programmable Ultra Low Power Timer for System Power Gating

Battery ➔ TPL5110 ➔ Low leakage switch ➔ DRV ➔ Sensors

35nA Power Consumption

Microcontroller (system) power supply is gated and switched On periodically

Done ➔ WiFi transceiver ➔ Sensors ➔ Microcontroller ➔ Done

35nA Power Consumption
Nanotimer Operation

- “OFF” Time Interval is set using an external resistor
- The system is periodically switched ON/OFF
- Microcontroller controls the “ON” time by sending a Done Signal to TPL device

![Diagram of Nanotimer Operation]

- **On Time**
- **Off Time**
- **100% system power consumption**
- **35nA system power consumption**
- **Time Interval (ex. 1 min)**
- **DRV signal**
- **Done (from μC) returns system to OFF Time**
Nanotimers in IoT Sensor Nodes

- IoT sensor nodes can measure environment with remote sensors. Periodically send data to central gateway.
- Operate in burst mode where system is asleep most of the time.
- Sleep Current -> Extremely important in determining battery life duration.
System Design without Nanotimer

Battery

Sensor

uC

Antenna Receives & Sends data from/to Central Gateway

System Design WITH Power Gating version of Nanotimer

Battery

TPL5110/ TPL5111

Low Leakage Switch

Sensor

uC

DONE

DRV

“OFF Time”

“ON Time”

Figure 2. A sensor node with an integrated system nano-timer

“OFF Time” minutes

Time Interval

Done (from μC) returns system to OFF Time

Figure 1. A typical sensor node
# TPL5110/5111

## Ultra-Low Power System Timer with Power Gating Functionality

### Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide Operating Voltage Range</td>
<td>1.8 to 5.5 V</td>
</tr>
<tr>
<td>Wide Operating Temperature Range</td>
<td>-40 to +105°C</td>
</tr>
<tr>
<td>Ultra-Low Supply Current</td>
<td>Normal operation 35nA</td>
</tr>
<tr>
<td>Programmable Timer Interval</td>
<td>100ms to 7200s</td>
</tr>
<tr>
<td>Precision</td>
<td>+/- 1% at 25, Rext @1% (IC only)</td>
</tr>
<tr>
<td>Drives ext MOSFET to power cycle remaining system</td>
<td></td>
</tr>
<tr>
<td>Manual Power ON of the mosfet</td>
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<tr>
<td>Small Package</td>
<td>SOT-23 6 pin</td>
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<tr>
<td>TPL5111 – inverted polarity for power gating</td>
<td></td>
</tr>
</tbody>
</table>

### Benefits

- Saves System Current
- Enables Cheaper Batteries
- Enables Longer Lifetime with Existing Batteries

### Applications

- Energy Harvesting Systems
- Power cycled applications
- Battery Management
- Remote Data-Logger
- Sensor Node
- Power-gating Applications
- Building Automation
- Low Power Wireless
- Consumer Electronics

![TPL5111 Circuit Diagram](image-url)
TPL5110/TPL5111 Timing

- Used as a low-power timer to power gate entire system for even further current consumption.
- DRV output: Control Signal for switch or EN pin of an LDO etc.
- Initially system is on until a DONE is received from µC.
- System and µC power on, processes information, sends a signal back to nanotimer
- When DONE is received, nanotimer turns off µC with DRV output
- If µC is stuck and no DONE received, nanotimer resets the µC last 50ms of timing interval.
# TPL5010
Ultra-Low Power System Timer with Watchdog functionality

<table>
<thead>
<tr>
<th>Features</th>
<th>Benefits</th>
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<tbody>
<tr>
<td>• Wide Operating Voltage Range 1.8 to 5.5 V</td>
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<tr>
<td>• Watchdog Function</td>
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<td>• Manual Reset</td>
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<tr>
<td>• Small Package SOT-23 6pin</td>
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</table>

## Applications
- Battery Powered, Duty Cycled Systems
- Fire, CO Alarms
- Occupancy Sensors
- Security Cameras
- Door Locks

![Diagram of TPL5010](image.png)
TPL5010 Timing

- Used as a low-power timer with watchdog functionality as substitute for µC’s power hungry internal timers during sleep.
- Issues a wakeup signal to µC at the beginning of selected timing interval
- µC wakes up from deep sleep, processes information, sends a signal back to nanotimer and goes back to deep sleep for rest of the timing interval
- If µC is stuck and no DONE received, nanotimer resets the µC.

Figure 8. Watchdog
Example: Pairing Nanotimers with TI MCU’s: **CC2650**

- **Assuming Constant Power:**
  - Standby Mode: 1μA of Current w/ Running LF Oscillator
Example: Pairing Nanotimers with TI MCU’s: **CC2650**

**TI Designs Number:** **TIDA-00374**

- Nano-timer paired with CC2650 MCU to duty cycle entire system: MCU retention/system wake up time is not important
- Instead of using CC2650 RTC in standby mode, can use nano-timer to program sleep intervals.
- Can directly compare:
  - CC2650 1µA Standby Current + Peripheral Standby Mode Currents **vs.** TPL 35nA Operational Current + System Leakage currents (~30 nA)
  - 16x Current Reduction!
TPL5110 test results: comparison of the topologies

Estimated Battery Life Comparison: TPL5110 Nano-Power System Timer versus CC2650 Standby Mode
Humidity & Temperature Sensing Node for Star Networks Enabling 10+ year Coin Cell Battery Life

**TI Designs Number:** TIDA-00374

### Solution Features
- HDC1000 humidity and temp digital sensing
- Configurable sleep time
- Power management partitioning for extremely low power consumption

### Solution Benefits
- Small, integrated solution size due to the integrated sensor and radio + mcu SoC
- Long Battery Lifetime: Designing for 10+ years off a single CR2032 coin cell battery

### Tools & Resources
- TIDA-00374 Tool folder
- User Guide
- Design Files: Schematics, BOM, Gerbers, Software, and more
- Device Datasheets:
  - HDC1010
  - TPL5110
  - TS5A3160
  - CC2650

[Diagram of the solution components:]
- CR2032 Coin Cell Battery
- TPL5110 (Nano-power system timer)
- TS5A3160 (Ultra-low leakage load switch)
- HDC1010 (Humidity and Temp. Sensor)
- CC2650 (ARM + Multi-Standard 2.4 GHz)
Humidity & Temperature Sensing Node for Sub-1 GHz Star Networks
Enabling 10+ Year Coin Cell Battery Life

**TI Designs Number:** TIDA-00484

**Solution Features**
- Configurable System Wakeup Interval
- Extremely low off-state current (270 nA for 59.97 seconds)
- Ultra low on-state current due to low active processor and radio transmit currents (3.376 mA for 30 ms)
- Extended transmit range due to Sub-1 GHz radio
- ±3% Relative Humidity Accuracy
- ±0.2°C Temperature Accuracy

**Solution Benefits**
- Use of Nano-Power System Timer to Duty-Cycle the System
  Results in 10+ year battery life from CR2032 coin cell
- Small, integrated solution size due to the integrated sensor and radio SoC

**Tools & Resources**
- TIDA-00484 Tools Folder
- User Guide
- Design Files: Schematics, BOM, Gerbers, Software, and more
- Device Datasheets:
  - HDC1010
  - TPL5111
  - TPS22860
  - TPS61291
  - CC1310
TPL5111 test results: comparison of the topologies

Estimated Battery Life Comparison: TPL5111 Nano-Power System Timer Versus CC1310 Standby Mode
## Nanotimers Product Family

<table>
<thead>
<tr>
<th></th>
<th>TPL5010</th>
<th>TPL5010-Q1</th>
<th>TPL5110</th>
<th>TPL5111</th>
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<td><strong>Pin/Package</strong></td>
<td>6SOT</td>
<td>6SOT</td>
<td>6SOT</td>
<td>6SOT</td>
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<tr>
<td><strong>Operating</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature Range</strong></td>
<td>-40 to 105</td>
<td>-40 to 125</td>
<td>-40 to 105</td>
<td>-40 to 105</td>
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<tr>
<td><strong>Approx. Price</strong></td>
<td>0.40</td>
<td>0.44</td>
<td>0.40</td>
<td>0.40</td>
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<td><strong>(US$$)</strong></td>
<td>1ku</td>
<td>1ku</td>
<td>1ku</td>
<td>1ku</td>
</tr>
</tbody>
</table>
HDC1080/HDC1010
Humidity & Temperature Sensor

Features

- Relative Humidity Range: 0% to 100%
- Humidity Accuracy: ±2%
- Typical Drift: < 0.5%/yr
- Avg. Supply Current (@1sps): 1.2uA
- Temperature Accuracy: ±0.2ºC
- Temperature Range (Operating): -20ºC to +85ºC
- Operating Voltage: 2.7V to 5.5V
- Packages
  - HDC1080: 6 pin DFN (3mm x 3mm)
  - HDC1010: 8 pin WLCSP (1.59mm x 2.04mm)

Benefits

- Completely integrated humidity and temperature IC provides guaranteed performance
- Fully calibrated sensor enables quick time-to-market
- Very low power consumption
- Small package size supports compact designs

Applications

- HVAC
- White goods (dryer, fridge, microwave, dishwasher)
- Printers
- Handheld Meters
- Camera Defog
- Smart Thermostats and Room Monitors
- Medical Devices
Always-On Low Power Gas Sensing with 10+ Year Coin Cell Battery Life

**Ti Designs Number:** TIDA-00756

### Solution Features

- Carbon monoxide gas sensor and analog logic always powered on to enable continuous monitoring and fast response times
- Bluetooth® Low Energy (BL) wireless connectivity reduces installation costs and allows multiple sensors to communicate with single host
- Self-check and end-of-life monitoring recognizes malfunctioning gas sensor and reports status every five minutes (configurable)
- Carbon monoxide gas detection range of 0 to 1000 ppm with ±15% accuracy

### Solution Benefits

- Use of nano-power analog ultra-low-power design resulting in 10-year battery life from single CR2032 coin cell
- Bluetooth® Low Energy (BL) wireless connectivity reduces installation costs and allows multiple sensors to communicate with single host

### Tools & Resources

- **TIDA-00756 Tools Folder**
- **User Guide**
- **Design Files:** Schematics, BOM, Gerbers, Software, and more
- **Device Datasheets:**
  - LPV811
  - TLV3691
  - TMP103
  - TPD1E0806
  - TPL5111
  - CC2650

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Agenda

• Always-On Vs. Power Cycled definition
• TI Nanopower Amplifier solutions for Always-on applications
• How to apply amplifiers in nanopower systems
  – Gas Sensing & PIR Motion Detection
  – Design Considerations
  – Power Cycling
• Using Nano-timers when Always-On is not feasible.
  – How to apply functionality & features of nanotimers to applications.
  – Where & why we win in Duty-Cycled systems.
    • Duty cycling & pairing with TI MCUs to reduce system power consumption
    • Low Power Humidity + Temp Sensing Products for Battery-Powered Applications
• Wrap-up
  – TI Nanopower Selection tools and getting help
### Products for Timers

**Nanotimers Selection Page**


#### Table of Timers

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Frequency (Max) (MHz)</th>
<th>VCC (Min) (V)</th>
<th>VCC (Max) (V)</th>
<th>IQ (Typ) (uA)</th>
<th>Special Features</th>
<th>Rating</th>
<th>Operating Temperature Range (C)</th>
<th>Package Group</th>
<th>Package Size (mm2/W x L (PKG))</th>
<th>Approx. Price (USD)</th>
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<tbody>
<tr>
<td>TPL5010-01</td>
<td>1.8</td>
<td>5.5</td>
<td>5.5</td>
<td>0.035</td>
<td>Low Power Timer, Watchdog Function, Programmable Delay Range, Manual Reset</td>
<td>Automotive</td>
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<td>8 mm2: 2.8 x 2.9(SOT)</td>
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<tr>
<td>TPL5111</td>
<td>1.8</td>
<td>5.5</td>
<td>5.5</td>
<td>0.035</td>
<td>Low Power Timer, MOS-Driven, Manual Reset, One-Shot Feature, Programmable Delay Range</td>
<td>Catalog</td>
<td>-40 to 105</td>
<td>SOT</td>
<td>8 mm2: 2.8 x 2.9(SOT)</td>
<td>0.40</td>
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</tr>
</tbody>
</table>
Where To Get Help with Operational Amplifiers

Selguide Tool

Parametric Search on ti.com

E2E Forum: http://ti.com/e2e

\[ \text{LME, OPA16xx, TPA, TAS, DRV} \quad \text{INA, OPA & LPV Devices} \]

\[ \text{TI Labs Videos and Training Material Help} \quad \text{LMH Devices (>50MHz)} \]

\[ \text{Everything Else!!} \]
Complete TI Amplifier Selection Tool
SelGuide

1. **Enter Requirements**
   Select package, temperature, output type, AC/DC parameters

2. **Compare Devices**
   Evaluate closest matches

Easy to install

Visit [www.ti.com/tool/opamps-selguide](http://www.ti.com/tool/opamps-selguide) or
ESP Keyword SEARCH “selguide”
(File name: Amplifier Product SelGuide Software)