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Achieving Millikelvin Temperature Stability

APPLICATION NOTE

ILX Lightwave®

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Achieving Millikelvin Temperature Stability

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Introduction

Many optoelectronic components and devices are sensitive to temperature fluctuations, which can affect their operating characteristics and lifetimes. When sensitive optoelectronics are used in a system, temperature control is often important to ensure proper operation and functioning. Diode lasers and non-linear crystals used in frequency doubling applications are examples of optoelectronic components that are particularly sensitive to temperature fluctuations.

Diode laser operating characteristics vary considerably with temperature. Emission wavelength, threshold current and operating lifetime are all strongly correlated to device temperature. For a typical diode laser emitting 3 mW at 780 nm, the emission wavelength will shift an average 0.26 nm/°C and the threshold current will change an average of 0.3 mA/°C. Table 1 shows typical wavelength sensitivity with regards to temperature in some common diode laser types. In addition to wavelength shift, the operating lifetime of a diode laser drops by a factor of two for every 20°C rise in operating temperature (see ILX Lightwave Application Note #33, Estimating Laser Diode Lifetimes and Activation Energy, for further discussion).

Table 1: Typical wavelength change due to temperature for common diode laser types

Laser Type	Wavelength Sensitivity
Fabry-Perot laser, GaAlAs	0.24 nm/°C
Fabry-Perot laser, InGaAsP	0.30 nm/°C
DFB laser	between 0.02 and 0.10 nm/°C

Thermoelectric coolers (TECs) can be used to provide a simple, reliable solution to precise temperature control in many applications of optoelectronic devices. Thermoelectric coolers can be used to heat or cool small components with a temperature range of ±40°C or more from ambient and have the capability to achieve temperature stabilities of better than 0.001°C. Because of their versatility, thermoelectric coolers are widely used in many standard optoelectronic packages. Additionally, TECs can be easily integrated into mounting fixtures to provide temperature control in specialized applications. However, without precise control of the thermoelectric cooler and proper consideration of factors effecting temperature stability, millikelvin temperature stability is difficult to realize.

This application note discusses the process of using a thermoelectric cooler controller, or TEC controller, and a thermoelectric cooler to achieve millikelvin stability in a test system. The system described in this application note was set up in a typical laboratory environment rather than in an environmental chamber to demonstrate that high stability is possible under real world conditions. The steps taken to incrementally improve temperature stability of the test setup are discussed. The process used to increase stability is general, such that a similar process can be adapted to achieve high temperature stability for components operating over a wide range of different conditions. Background information on causes of temperature instability and operation of TEC controllers is presented to preface the discussion of experimental results.

Causes of Temperature Instability

Two important sources of temperature change must be mitigated in order to achieve maximum stability: device sources and environmental sources. Device sources of temperature variation are due to normal operation of the device under test. In many optoelectronic components, such as laser diodes, heat is created during normal operation, causing a thermal load that leads to temperature changes. Large or rapid changes in operating current may increase thermal load significantly and lead to temperature instability. Smaller thermal loads require less power and less time to be temperature stabilized compared to larger thermal loads. This means that stable and well-controlled device current is important to achieving the best possible temperature stability.

Environmental sources of temperature variation arise from the device's operating environment. Significant shifts in room temperature in a laboratory often occur due to air conditioner cycling or even because of changes in sunlight entering the room. Moreover, other equipment and devices operating in laboratory environments can create significant thermal and electrical loads which must be isolated from the device under test. Compounding these effects, air currents due to foot traffic and the opening and closing of doors and windows can cause additional, unwanted changes in thermal load. Without controlling environmental sources of thermal load the highest stability levels cannot be reached.

Selecting System Components

The instruments and devices used to develop a system should be selected based upon the end goal. In the experiment described in this application note, the goal was temperature control with sub-millikelvin stability. The major components of our system are our TEC controller, temperature sensor, device under test, and mount setup.

The TEC controller used can have a number of different control loop types with different levels of signal processing involved. Generally more processing of the feedback system allows for more versatile TEC controller functionality. This versatility is controlled through user input of parameters to fine tune the feedback loop. This requires the user to measure performance and tweak the control loop parameters until the desired behavior is achieved. This extra effort to achieve finer control is not always necessary and in these cases a TEC controller with a less complicated feedback system is sufficient.

For our application, where high stability is desired, a TEC controller with a full digital proportional-integral-derivative, or PID, control loop was used. Digital PID control requires more user modification, but allows for maximum flexibility and adjustment of the control loop and the resulting temperature control behavior. PID control is discussed in greater detail later in this application note.

Selection of an appropriate temperature sensor is also important to system performance. Various types of sensors exist for converting temperature into an electrical signal which can be interpreted by instruments. The major characteristics that determine which type of sensor to use are the measurement accuracy, stability, linearity, and sensitivity. The most common types of sensors used in laboratory applications are thermistors, resistive temperature devices (RTDs), IC temperature sensors, and thermocouples; each of these sensors has different strengths and weaknesses in terms of the four measurement characteristics. Thermistors have high measurement sensitivity, making them ideal for detection of small temperature changes. In this experiment it was important to detect millikelvin changes in temperature and so thermistors were selected to be used as the temperature sensors.

The final component to consider is the mount setup. The importance of the mount is not only to hold the device under test in place and thermally connect it to the TEC module, but also to act as an effective heat sink. A heat sink allows for excess heat to be coupled efficiently away from the device under test. Two factors that must be considered in selecting a heat sink are its thermal impedance and its thermal time constant. The thermal impedance determines the temperature rise at the heat sink surface for a given amount of heat transferred. For example, a typical 3" x 3" finned heat sink will have about a 1.8°C rise in temperature for every watt of thermal energy dissipated onto its surface. This temperature rise limits the range of temperature control for the device under test.

In achieving millikelvin temperature stability, the thermal time constant of the heat sink also plays a critical role. The thermal time constant is a number that represents how quickly the system responds to changes in ambient temperature. A system with a high thermal time constant responds slowly to temperature changes and a system with a small thermal time constant responds quickly to temperature changes.

Common finned heat sinks often have relatively low thermal impedance and a small thermal time constant, resulting in a high sensitivity to changes in room air currents and ambient temperature. Alternatively, a heat sink with a large thermal time constant reduces short-term sensitivity to the environment and allows the temperature control loop to achieve maximum performance. Due to this consideration, the mount in the application described here was bolted to a large metal optical table. This increased the mount's thermal time constant and buffered the load from room temperature variations. Finally, during testing, the high area heat sink surface of the mount was insulated from air currents to further limit coupling to the environment.

Millikelvin Stability Test Setup

As discussed earlier, a TEC controller with full digital PID control was determined to be the best choice for this application because of the adjustability this control system offers. The ILX Lightwave LDT-5980 was selected to be used as the TEC controller. Although the temperature stability for the LDT-5980 is specified at ±0.005°C, it was believed that the experimental procedure would allow for finer temperature control. The LDT-5980 was used to control the internal TEC of an ILX Lightwave LDM-4984T Temperature Controlled Butterfly Laser Diode Mount. As discussed, the LDM-4984T mount was screwed down to a metal optical table.

A test load that allowed for independent temperature measurement by two sensors was used in order to verify temperature stability. This test load was prepared by drilling a small hole through a small aluminum block (5mm x 10mm x 15mm) and securing two thermistors adjacent to one another inside the block with thermal epoxy, as shown in Figure 1. The test load was mounted on the LDM-4984T mount. Thermistor 1 was used as the temperature feedback sensor for the LDT-5980 and thermistor 2 was connected to an Agilent 34401A 6½ digit multimeter to provide an independent measurement of the temperature of the test load. A second Agilent 34401A 6½ digit multimeter was connected to a third thermistor, thermistor 3, to provide monitoring of room temperature. The test setup is diagramed in Figure 2.

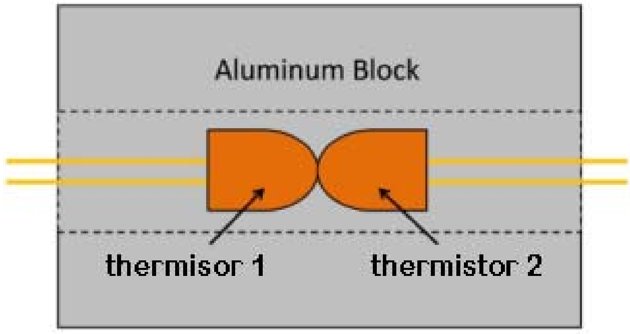


Figure 1: Internal view of the test load showing adjacent thermistors

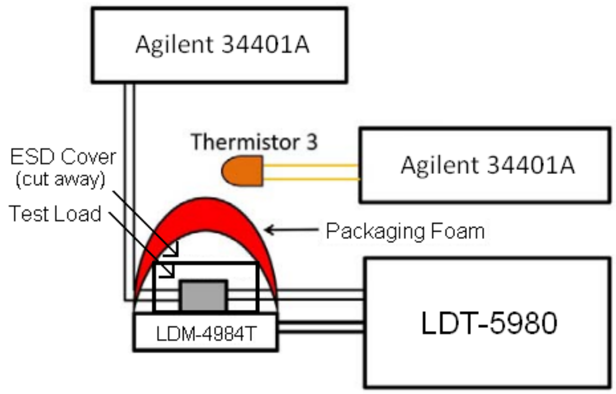


Figure 2: Experimental setup for temperature stability testing

In order to insulate the load from air currents, changes in room temperature and nearby equipment, various types of insulating materials were added to the test setup over the course of testing. To begin, the test load was simply placed on the mount and clamped in place, a setup which offered very little insulation. The electrostatic discharge (ESD) protection cover of the LDM-4984T mount was then placed over the test load, offering some insulation. Finally, to further insulate the load, packaging foam was then placed over the ESD cover and secured in place with packaging tape. The fully insulated load is diagramed in Figure 2.

Optimizing the Test Setup

Selecting the proper components gave a good basis for beginning testing of temperature stability, but further work was required to achieve millikelvin stability. Two methods were used to arrive at the best results: changing PID control loop coefficients and increasing insulation of the test load. Since optimal PID constants will change as the thermodynamic properties of the system change, the PID was tuned to offer the best stability with the maximum insulation in place.

PID loops are controlled by altering three PID control loop constants. These constants are called K_P, K_I, and K_D. The initial values for the K_P, K_I, and K_D terms were arrived at using the built-in auto-tune function of the LDT-5980 TEC controller. The values found by this algorithm were $K_P = 39.89$, $K_I = 0.035$, and $K_D = 1.2$. The auto-tune algorithm was designed to give PID values which balance the two goals of having the load quickly reach to the temperature setpoint and also stay stable. Since in our application high stability at the cost of speed to setpoint was acceptable, the PID constants were modified to arrive at a more appropriate response.

The ideal K_P, K_I, and K_D terms can be determined experimentally or through consideration of the typical effects of changing each term. The most effective method of changing the terms is a mix of experiment and theory, which takes the measured data and uses theoretical reasoning to determine the most practical changes to make. Based on the PID control theory as described in ILX Lightwave Application Note # 20, *PID Control Loops in Thermoelectric Temperature Controllers*, and on experimental results, the PID control loop was progressively modified to reach maximum stability.

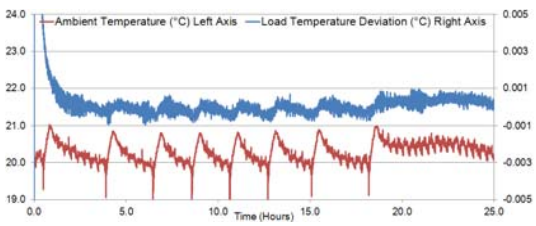
The theory of PID control involves many considerations, but the pertinent ideas can be understood by considering the role of each of the three terms. Increasing the K_P term causes the setpoint temperature to be reached more quickly. The K_I term helps control error that lasts for long periods of time. The K_D term allows the control loop to better respond to short-term error signals. K_P and K_I terms that are very high can lead to temperature oscillations, and lowering the higher of the two terms until oscillations cease is an effective way to eliminate this behavior.

In this experiment an iterative process was used to alter the K_P, K_I, and K_D terms. The results are summarized in Table 2, and graphs of the data collected during this process are shown in Figure 3. For test runs 1, 2, 3, and 4 the major change involved lowering the K_P term significantly until the rapid temperature oscillations were reduced. The changes to K_P were determined to be the best method for reducing rapid oscillations by considering the theory discussed above. The theory was confirmed by noting that changes to K_I and K_D made during these test runs were found to have little impact. Despite the overall stability decrease seen in these test runs as K_P was lowered, the reduction of oscillations is necessary to achieve high stability. Because of this, the K_P term was lowered until oscillations ceased. For test run # 4 K_P was set to 4.00, and the high-frequency oscillations were no longer present.

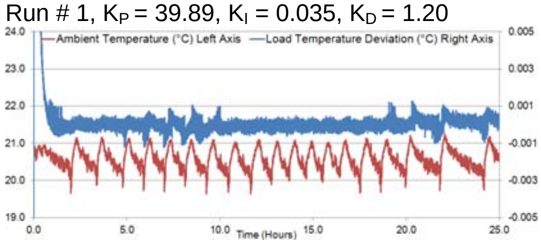
During test run # 4 several transient temperature spikes were noted. These were significantly larger than the normal temperature variation due to room temperature changes. The cause of these spikes was determined to be electromagnetic interference in the system arising from a CRT computer monitor placed near the test setup in the lab. Turning this monitor off was found to eliminate these temperature spikes. However, to show that modification of the PID loop could allow the system to remain stable despite this EM interference, the monitor was left turned on for test run # 5 and the K_D term was increased from 0.00 to 0.04. The higher K_D term allowed the system to quickly compensate for these short lived temperature spikes, resulting in sustained millikelvin stability. To show that stability could be increased even further as more of the external conditions were controlled, another experiment was performed.

Table 2: Stability change with PID constants

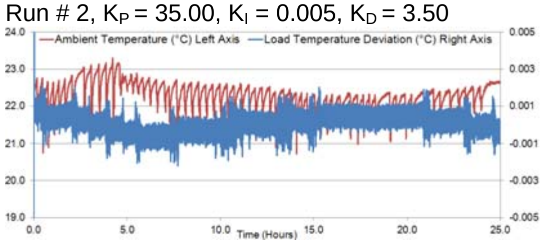
Test Run #	PID Settings	Load Temp Stability
1	$K_P = 39.89$, $K_I = 0.035$, $K_D = 1.20$	< ±0.0015°C
2	$K_P = 35.00$, $K_I = 0.005$, $K_D = 3.50$	< ±0.0020°C
3	$K_P = 8.00$, $K_I = 0.800$, $K_D = 0.00$	< ±0.0025°C
4	$K_P = 4.00$, $K_I = 0.400$, $K_D = 0.00$	< ±0.0035°C
5	$K_P = 4.00$, $K_I = 0.400$, $K_D = 0.04$	< ±0.0007°C



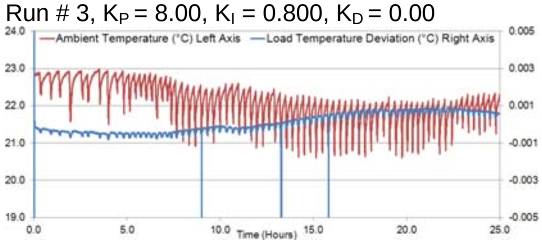
Run # 1, $K_P = 39.89$, $K_I = 0.035$, $K_D = 1.20$



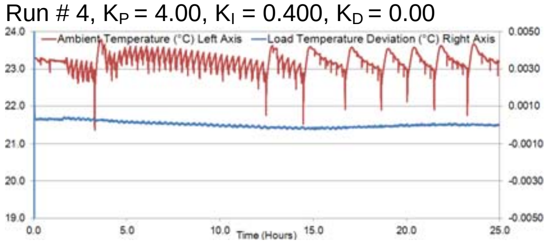
Run # 2, $K_P = 35.00$, $K_I = 0.005$, $K_D = 3.50$



Run # 3, $K_P = 8.00$, $K_I = 0.800$, $K_D = 0.00$



Run # 4, $K_P = 4.00$, $K_I = 0.400$, $K_D = 0.00$



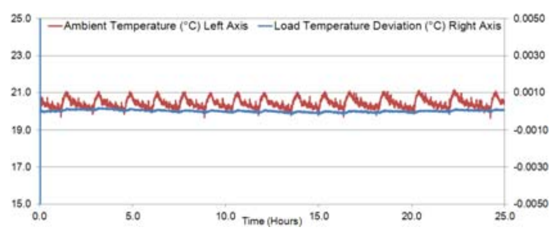
Run # 5, $K_P = 4.00$, $K_I = 0.400$, $K_D = 0.04$

Figure 3: Data collected for temperature stability during PID optimization process

For the final test run, test run # 6, the overhead lights and the CRT monitor running in the laboratory were turned off to eliminate EM interference. The laboratory thermostat was set to a lower temperature to lessen large changes in ambient temperature caused by the air conditioner. Finally, the K_P, K_I, and K_D constants were all increased by 25%. Increasing all the constants by a relatively small and equal percentage in this way can often result in tighter temperature control. The combined result was even better temperature stability. However, in this case we only increased stability by 0.2 millikelvin beyond the stability seen in test run #5. This demonstrates that even with all of these interventions only slightly better performance is possible. At this point any further increase in stability would be very difficult without the use of a second level of temperature control. The results of test run #6 are shown in table 3 and figure 4.

Table 3: Temperature stability found with environmental thermal load controls in place

Test Run #	PID Settings	Load Temp Stability
6	$K_P = 5.00$, $K_I = 0.500$, $K_D = 0.05$	< ±0.0005°C



Run # 6, $K_P = 5.00$, $K_I = 0.500$, $K_D = 0.05$

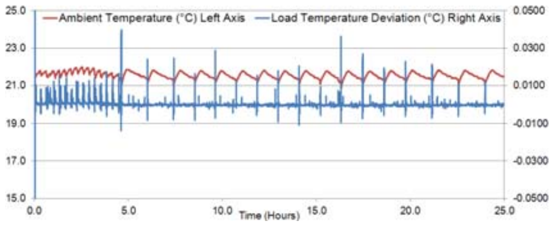
Figure 4: Data collected for temperature stability with environmental thermal load controls in place

To demonstrate the importance of the insulation in achieving the high temperature stability, several test runs were performed at the optimal PID constants from test run # 6 above but with varying levels of insulation used to isolate the test load. The results of these tests are presented in Figure 5 and Table 4.

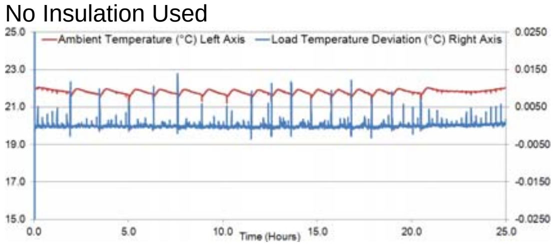
Table 4: Temperature stability found with various insulating materials

Insulation Type	Room Temperature Range (°C)[1]	Room Temperature Swing(°C)[1]	Load Temperature Range(°C)[2]	Load Temperature Swing(°C)[2]
No Insulation	20.66 – 21.99	±0.665	25.133 – 25.187	±0.0270
ESD Cover Only	20.92 – 22.04	±0.560	25.143 – 25.160	±0.0085
ESD Cover and Open-Cell Foam	20.65 – 23.93	±1.640	25.146 – 25.154	±0.0040
ESD Cover and Closed-Cell Foam	19.63 – 21.14	±0.755	25.145 – 25.146	±0.0005

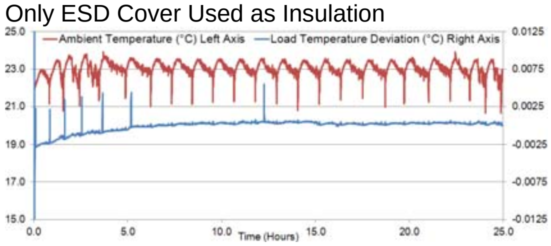
1: Measured with Agilent 34401A through thermistor 3
2: Measured with Agilent 34401A through thermistor 2



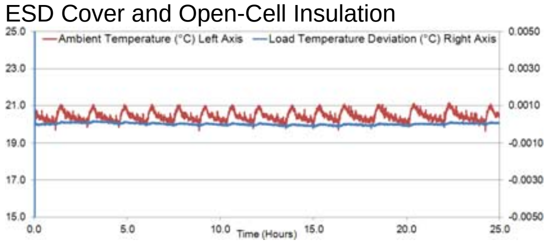
No Insulation Used



Only ESD Cover Used as Insulation



ESD Cover and Open-Cell Insulation



ESD Cover and Closed-Cell Insulation

Figure 5: Stability with different insulation

Note that the load temperature deviation is plotted on increasingly magnified scales due to the increase in temperature stability between test runs. Also note that this increasing stability is achieved despite the ambient temperature changes which occurred during the last two test runs being greater than changes which occurred during the first two test runs.

Conclusions

These results show that millikelvin temperature control stability can be achieved with optoelectronic components operating in a laboratory setting. While it is not practical to completely control the environment in a functioning laboratory, many aspects of the temperature control system and the environment are controllable. The control loop, insulation of the device being temperature controlled, room air conditioning, and the presence of high thermal and electrical loads in the laboratory were shown to have an effect on stability. As more of these factors are controlled, greater stability becomes possible. This is seen in test run # 6, where all of these factors were controlled and the highest measured stability was demonstrated.

If the temperature control system is set up properly and the components chosen well, millikelvin stability is possible while only controlling a few external factors. This is seen in test run # 5, where only insulation and control loop functioning were controlled and the rest of the laboratory environment was not altered. In this experiment, using a full PID control loop and some simple insulation, sub-millikelvin stability was reached by careful tuning of the PID control loop parameters.

The process for tuning the PID loop described in this application note is general; it can be used to achieve similar results in a variety of test setups involving different loads operating under real world environmental conditions, such as those found in a laboratory or on the floor of a manufacturing plant.

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