

TEC control for laser wavelength stability

From a channel tolerance to a thermistor reading, a TEC rating and controller gains

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1. The short answer, up front

A laser's wavelength follows its chip temperature, so a wavelength tolerance is really a temperature tolerance. A 1550 nm DFB laser that must stay within ± 2.5 GHz of its channel may move only ± 20.0 pm, which at 0.10 nm/K is ± 200 mK of chip temperature. The controller holds the thermistor, not the chip, so most of that budget goes to the thermal gap between the two.

In the worked example (0.25 A drive, 25 °C set point, 45 °C case) 0.360 W of drive heat crosses 0.25 K/W, so the chip sits 90 mK above the thermistor. With its drive-heat variation the gap takes 103.5 mK, 52 % of the window and 73 % of all the error terms I can quantify. Those terms add to 142 mK untrimmed and 27 mK once the set point is trimmed against a wavelength reading. The TEC needs 0.387 A and 0.833 V, 17.3 % of its capacity, and a PI controller tuned from a step test holds a 1 K/min ambient ramp to 4.6 mK. The heat-load numbers match the TEC heat load calculator at jezdangomez.com/calculators/tec-heat-load/ digit for digit.

2. From wavelength tolerance to temperature budget

A channel is specified in frequency, the laser tunes in wavelength, and the temperature controller works in kelvin, so the budget needs two conversions. The first is the wavelength interval that corresponds to a frequency tolerance:

$$\Delta\lambda = \frac{\lambda^2 \Delta\nu}{c} \quad (1)$$

At 1550 nm one gigahertz is 8.014 pm, so ± 2.5 GHz is ± 20.0 pm. The second conversion divides by the tuning coefficient $k = d\lambda/dT$ from the laser datasheet:

$$\Delta T_{\text{chip}} = \frac{\Delta\lambda}{k} \quad (2)$$

For a DFB laser at 0.10 nm/K, ± 20.0 pm is ± 200 mK. Put the other way, a DFB tunes 12.48 GHz per kelvin, so the whole ± 2.5 GHz channel is a fifth of a kelvin on each side. A VCSEL at 0.06 nm/K would allow ± 334 mK for the same wavelength window, and a Fabry-Perot gain peak at 0.24 nm/K only ± 83 mK (Figure 1).

The coefficient is a device property, so it is an input. It comes from the refractive index of the grating region: $d\lambda/dT \approx (\lambda/n)(dn/dT)$, the step Kasap takes for a cavity mode [1]. With $n \approx 3.2$ and $dn/dT \approx 2 \times 10^{-4} \text{ K}^{-1}$ (typical orders for a III-V waveguide, my assumption) that gives 0.097 nm/K, consistent with 0.10; Kasap quotes 0.06 to 0.1 nm/°C for DBR lasers and about 0.05 nm/°C for VCSELs [1]. Use the figure on your own datasheet.

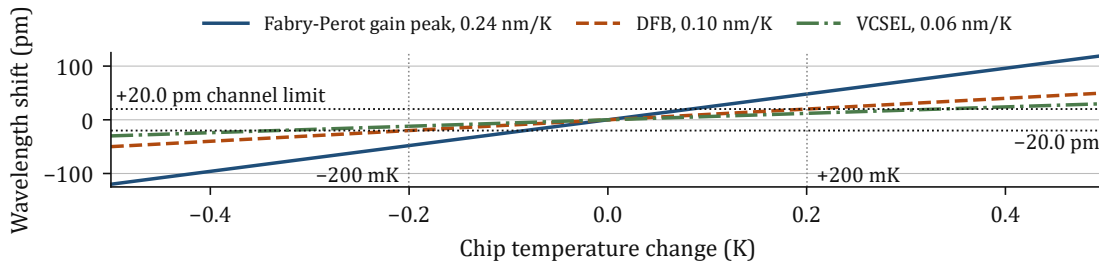


Figure 1. Wavelength shift against chip temperature change for tuning coefficients of 0.24, 0.10 and 0.06 nm/K. Dotted horizontal lines: the ± 20.0 pm limit of a 1550 nm laser held to ± 2.5 GHz; dotted vertical lines: the DFB budget of ± 200 mK.

Read ± 200 mK as the allowance for temperature alone, and as a limit on a chip that nobody measures; section 3 shows how far that chip is from the sensor.

3. Where the temperature error comes from

The control loop closes on the thermistor; which is bonded to the cold plate. The chip is on a submount a few millimeters away, and everything the chip dissipates has to cross that gap on its way to the cold plate (Figure 2). For this module the thermal resistance from chip to thermistor is 0.25 K/W. Of the 0.400 W the laser draws, 0.040 W leaves as light, so 0.360 W of heat crosses the gap and the chip runs 90 mK warmer than the sensor reads. That is 9.0 pm of wavelength, and it moves whenever the drive current or the mount changes. Each additional 0.10 K/W of gap costs 36 mK at this drive.

The gap is the largest of seven terms (Table 1). The thermistor heats itself: 0.100 mW at 100 μ A, into a mount that sheds 4 mW/K, reads 25 mK high, so the controller cools the plate by that much and the chip ends up that much colder. The ADC cannot resolve better than one count, 0.99 mK at this bias (section 5). Integral action removes the steady-state error for a fixed set point, but a drifting ambient leaves a ramp error that depends on the tuning, and a sudden change leaves a transient (section 6).

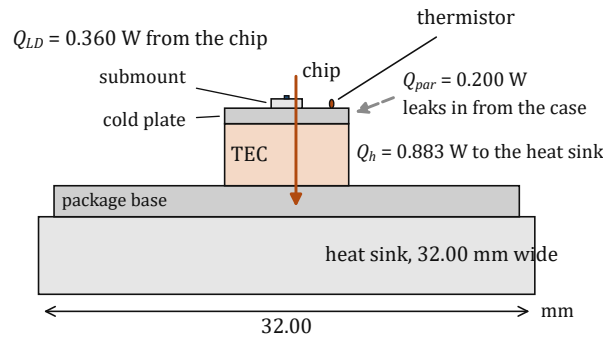


Figure 2. Thermal stack of the example module, drawn to scale across and enlarged 2:1 vertically. The package base is 30 mm wide, the TEC and cold plate 8 mm, the submount 2.0 mm and the chip 0.3 mm; the heat sink is 32.00 mm wide. The arrow is the heat path from the chip to the heat sink; the thermistor sits on the cold plate beside the submount.

Table 1. Error budget for the 1550 nm DFB example, as chip temperature error in millikelvin against a window of ± 200 mK. “Trimable”: a one-time shift of the set point against a wavelength reading removes the term. Totals are summed before rounding.

Term	Basis	mK	Trimable
Chip to thermistor gradient at the operating drive	0.25 K/W $\times$ 0.360 W	90.0	yes
Gradient change with drive heat	± 15 % of the drive heat (assumed)	13.5	no
Thermistor self-heating	100 μ A, 4 mW/K mount	25.0	yes
Self-heating change with the mount	± 20 % mount dissipation (assumed)	6.2	no
ADC resolution	half an LSB, 16 bits over 2.5 V	0.5	no
Bias-current reference drift	100 ppm of 1.00 V (assumed)	2.6	no
Controller error in an ambient ramp	tuned PI, 1 K/min case ramp (section 6)	4.6	no
Sum of all terms, nothing trimmed	worst case, all the same sign	142.5	
Sum after one trim of the set point	terms marked “no”	27.5	

Read the table in two passes. Untrimmed, the terms add to 142 mK, or 71 % of the window, leaving 58 mK for everything not listed. The gradient and the self-heating are offsets, so one trim of the set point against a wavelength

reading removes them; the net offset here is +65 mK, chip above reading. What remains, 27 mK or 14 % of the window, is the part that moves. Sensor calibration is not in the table: it sets where the chip sits, not how steadily it holds there, and the same trim absorbs it.

4. Heat load, and TEC capacity and drive

The TEC has to pump everything that reaches the cold stage: the laser's heat, the heat that leaks in from the case, and the thermistor's own dissipation. Light that leaves the module takes its energy with it, so the laser term is electrical input minus optical output:

$$Q_c = Q_{LD} + Q_{par} + P_{sh} \quad Q_{par} = \frac{T_{case} - T_{set}}{R_{par}} \quad (3)$$

with $Q_{LD} = I_{LD}V_f - P_{opt} = 0.250 \text{ A} \times 1.600 \text{ V} - 40 \text{ mW} = 0.360 \text{ W}$, $Q_{par} = (45 - 25) \text{ K} / 100 \text{ K/W} = 0.200 \text{ W}$ through leads, gas and pigtail, and $P_{sh} = I_b^2 R_{th} = 0.100 \text{ mW}$. The total is $Q_c = 0.560 \text{ W}$.

The TEC is described by three effective properties, the Seebeck coefficient S , the electrical resistance R and the thermal conductance K , derived from the three numbers on its datasheet [2]:

$$S = \frac{V_{max}}{T_{h,ref}} \quad R_{TEC} = \frac{V_{max}(T_{h,ref} - \Delta T_{max})}{T_{h,ref}I_{max}} \quad (4)$$

$$K_{TEC} = \frac{V_{max}I_{max}(T_{h,ref} - \Delta T_{max})}{2T_{h,ref}\Delta T_{max}} \quad Q_{max} = \frac{V_{max}I_{max}(T_{h,ref} + \Delta T_{max})}{2T_{h,ref}} \quad (5)$$

The datasheet maxima are $I_{max} = 1.8 \text{ A}$, $V_{max} = 3.6 \text{ V}$ and $\Delta T_{max} = 70 \text{ K}$ at a hot side of $T_{h,ref} = 300 \text{ K}$, which give $S = 12.000 \text{ mV/K}$, $R_{TEC} = 1.5333 \Omega$, $K_{TEC} = 35.49 \text{ mW/K}$ and $Q_{max} = 3.996 \text{ W}$. Temperatures here are absolute. At the cold side T_c the pumped heat is a quadratic in the current, and the working current is its smaller root:

$$Q_c = SIT_c - \frac{1}{2}I^2R - K\Delta T \Rightarrow I = \frac{b - \sqrt{b^2 - 2Rc}}{R} \quad (6)$$

where $b = ST_c$, $c = Q_c + K\Delta T$, and a negative current means the TEC is heating. The voltage, electrical power and hot-side heat follow, and a heat sink with resistance R_{hs} makes the case temperature depend on the answer, so it is iterated until the case moves by less than a microkelvin:

$$V = S\Delta T + IR \quad P = IV \quad Q_h = Q_c + P \quad T_{case} = T_{amb} + Q_h R_{hs} \quad (7)$$

For the example, $\Delta T = 20.00 \text{ K}$, $I = 0.387 \text{ A}$ (21.5 % of I_{max}), $V = 0.833 \text{ V}$, $P = 0.323 \text{ W}$, $Q_h = 0.883 \text{ W}$ and $\text{COP} = 1.74$, in 1 iteration because $R_{hs} = 0$ holds the case at ambient. With a 1.5 K/W heat sink the case rises to $46.40 \text{ }^\circ\text{C}$ in 6 iterations, the current to 0.409 A and the heat to reject to 0.935 W : a poor heat sink costs current and capacity.

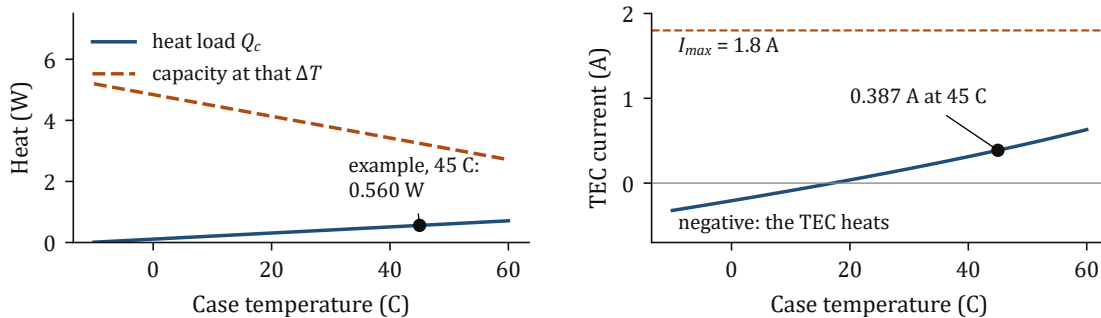


Figure 3. Heat load and TEC current for the example against case temperature, with the set point held at $25 \text{ }^\circ\text{C}$ and the case at ambient ($R_{hs} = 0$). Left: the load Q_c and the capacity at the temperature difference that results. Right: the current, negative where the case is colder than the set point and the TEC has to heat.

Judge the load against the capacity at the temperature difference you will run, not Q_{max} , which holds only at $\Delta T = 0$. At 20 K the capacity with the current limited to I_{max} is 3.246 W , so the 0.560 W load is 17.3 % of it. Across ambient

(Figure 3) the current reverses at a case temperature of 17.1 °C, where the leak and the laser heat no longer need pumping, and at 60 °C the TEC runs 0.631 A at $\Delta T = 35$ K and 26.2 % of capacity. The calculator flags a load above 70 % of capacity or a temperature difference above 25 K, where the constant-property model and the margin for a hot day are both thin; at 60 °C the example is past the 25 K mark, well inside capacity but a case to measure. In Figure 4 the quadratic term bends every curve over, so at high current extra amperes buy little.

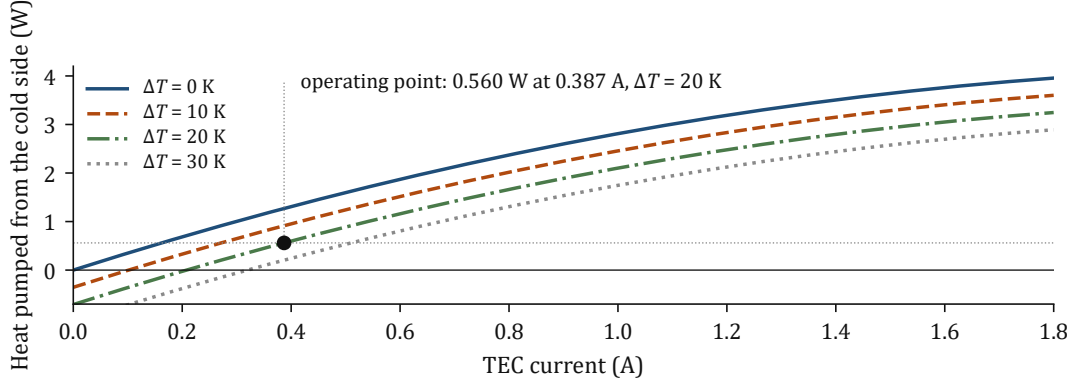


Figure 4. Heat pumped from the cold side against TEC current at four temperature differences, from the model of Eq. (4) to (6) with $S = 12.000$ mV/K, $R = 1.5333 \Omega$ and $K = 35.49$ mW/K at a 25 °C cold side. The dot is the operating point of the worked example.

5. Sensor choice and placement

Three sensor types are common (Table 2). For a laser loop the NTC thermistor is the usual choice, because its signal is large: a 10 k Ω part with $\beta = 3435$ K changes 3.86 % per kelvin, where a platinum RTD changes 0.385 %, a tenth of that. At the same 100 μ A bias the 10 k Ω thermistor gives 38.6 mV/K against 0.385 mV/K for a Pt1000, about 100 times more (Table 2). The beta equation is the two-parameter reduction of the Steinhart-Hart fit [4], $1/T = A + B \ln R$ with the cubic term dropped:

$$R(T) = R_{25} \exp\left(\beta \left(\frac{1}{T} - \frac{1}{298.15}\right)\right) \quad \frac{dR}{dT} = -\frac{\beta R}{T^2} \quad (8)$$

At 25 °C and 10 k Ω the slope is $-386 \Omega/\text{K}$. A β quoted between 25 and 85 °C averages the curve over 60 K, so the local slope at the set point can differ from this by a few percent. That error does not propagate into the loop, because the controller gain comes from the step test in section 6, which measures the true slope.

Table 2. Three ways to sense the cold stage. The NTC is the 10 k Ω example, the RTD a Pt1000 at the same 100 μ A bias, and the IC sensor a typical analog part read by the same converter:

	NTC thermistor	Pt RTD	Silicon IC sensor
Sensitivity at 25 °C	$-386 \Omega/\text{K}$ ($-3.86 \text{ \%}/\text{K}$)	$+3.85 \Omega/\text{K}$ ($+0.385 \text{ \%}/\text{K}$)	not applicable
Signal at 100 μ A	$-38.6 \text{ mV}/\text{K}$	$+0.385 \text{ mV}/\text{K}$	10 mV/K, typical analog part
One ADC count (16 bits, 2.5 V)	0.99 mK	99 mK	3.8 mK at 10 mV/K

The bias current trades signal against self-heating. At 100 μ A the thermistor drops 1.00 V and dissipates 0.100 mW; the signal is 38.6 mV/K, so the ± 200 mK budget is ± 7.7 mV at the ADC input. A 16-bit converter over 2.5 V resolves 38 μ V, which is 0.99 mK. At 10 μ A the self-heating falls to 0.25 mK but one count becomes 9.9 mK; at 300 μ A a count is 0.33 mK but the self-heating is 225 mK, and its change with the mount grows in proportion. A 100 μ A bias is a fair middle for a 16-bit converter; more resolution lets you lower it.

Placement sets the gap of section 3. Bond the bead to the cold plate as close to the submount as the mechanical design allows, with thermal epoxy under its full footprint and fine leads anchored to the plate. Every 0.10 K/W between bead and chip is 36 mK at this drive. Never put the sensor on the hot side of the TEC: the loop would regulate

the wrong face, with the 20 K across the TEC unseen between sensor and laser. On the module of Figure 5 the thermistor is on pins 2 and 5 and the TEC on pins 1 and 14, so pin 2 sits right beside TEC+: route the sense pair away from the TEC pair, because 1 mV of pickup on a 38.6 mV/K signal is 26 mK.

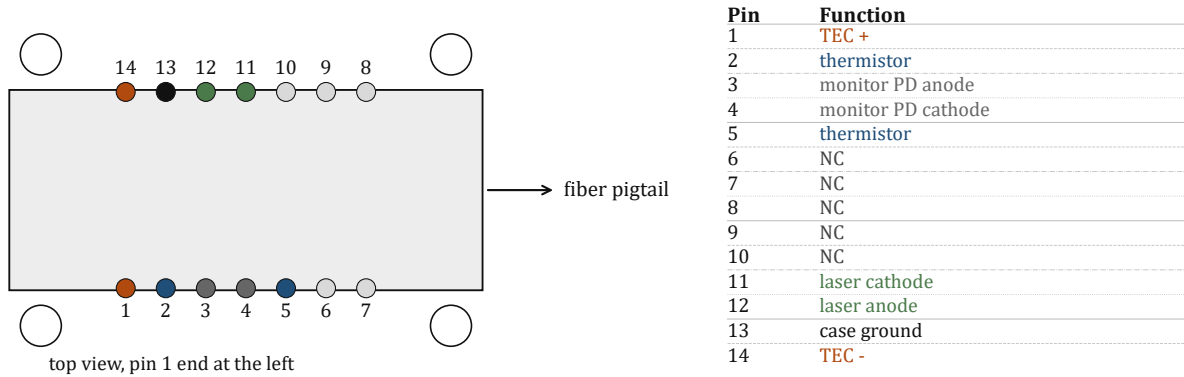


Figure 5. The generic 14-pin butterfly module of this note, top view, with its pinout. The thermistor is on pins 2 and 5 and the TEC on pins 1 and 14. This is the pinout of this module; there is no single industry standard for 14-pin butterfly pinouts, so check the datasheet of the module you use.

6. Controller settings from a step test

The method needs only the TEC driver in current mode and a thermistor readout that logs. With the loop open at the operating point, step the TEC current, record the thermistor until it settles (five time constants), and fit a first-order response with dead time: a gain K_p in K/A, a time constant τ and a dead time L . This note has no bench, so **the step test below is simulated**: the nonlinear heat balance of the cold stage (heat capacity 0.20 J/K, the TEC of section 4, the leak, a 0.3 s sensor lag) is stepped by +0.10 A and read through a 16-bit ADC. On hardware the recorded trace replaces mine and nothing else changes.

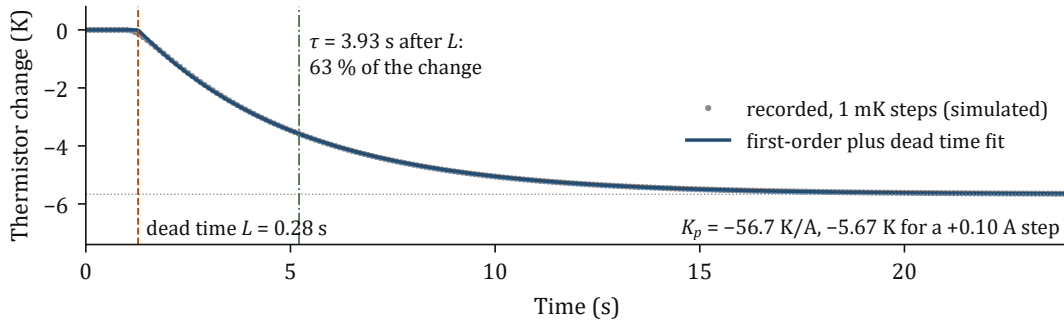


Figure 6. Simulated step test: the thermistor reading after a +0.10 A step in TEC current at the operating point, with the loop open. The dots are the nonlinear model read through a 16-bit ADC, one count 0.99 mK; the line is the first-order plus dead time fit. This trace is simulated; on hardware the recorded trace takes its place.

The fit (Figure 6) gives $K_p = -56.7$ K/A, $\tau = 3.93$ s and $L = 0.28$ s; the thermistor ends -5.66 K from where it started, and the fit follows the 0.99 mK steps to 10 mK rms. The sign is negative because more current cools. The dead time is not a transport delay; it stands in for the sensor lag, which a first-order fit cannot represent separately. Linearizing the heat balance about the operating point gives the same plant analytically:

$$C \frac{d\Delta T}{dt} = -G\Delta T - (ST_c - IR)\Delta I \quad G = \frac{1}{R_{\text{par}}} + SI + K \quad \tau = \frac{C}{G} \quad (9)$$

which predicts $K_p = -59.5$ K/A and $\tau = 3.99$ s. The step reads a little low because a 0.10 A step is large enough that the TEC's I^2R term bends the response; use a smaller step if the cold stage tolerates a smaller signal. The time constant is shorter than $C/K = 5.64$ s because the cold stage loses heat through three parallel paths, not one: the TEC's

conductance (35.5 mW/K), the parasitic leak (10.0 mW/K) and the Peltier term SI (4.6 mW/K), which together make $G = 50.1$ mW/K.

The tuning rule is SIMC, the simple internal model control rules of Skogestad [3]. For a first-order plant with dead time and a PI controller:

$$K_c = \frac{\tau}{K_p(\tau_c + L)} \quad \tau_I = \min(\tau, 4(\tau_c + L)) \quad (10)$$

τ_c is the closed-loop time constant you choose: Skogestad recommends $\tau_c = L$ for tight control and a larger value for robustness. With the error defined as set point minus reading, K_c carries the sign of K_p and is negative. Table 3 compares three choices on the nonlinear model. I use $\tau_c = L$: $K_c = -0.125$ A/K and $\tau_I = 2.22$ s. It is the best at rejecting ambient change, which is the term that eats the budget, and the price is a 195 mK overshoot on a 1 K set-point step, which a slow set-point ramp or set-point weighting removes. Against the linearized plant with its sensor lag the loop has a phase margin of 56° and tolerates 0.58 s of extra delay at its 1.70 rad/s crossover. One millikelvin of sensor noise becomes 0.13 mA of TEC current, which is harmless.

Table 3. SIMC settings for three choices of the closed-loop time constant τ_c with the fitted K_p , τ and L of Figure 6, and the simulated result of each on the nonlinear model. Overshoot and settling are for a +1 K set-point step (settling to ± 10 mK); the peak is for a +1 K step of case temperature; the ramp error is for a 1 K/min case ramp.

$\tau_c =$	τ_c (s)	K_c (A/K)	τ_I (s)	Overshoot (mK)	Settle (s)	Case-step peak (mK)	Ramp error (mK)
$\tau/2$	1.97	-0.031	3.93	0	7.9	255	33.3
$\tau/4$	0.98	-0.055	3.93	1	3.5	183	18.7
L (used)	0.28	-0.125	2.22	195	5.2	108	4.6

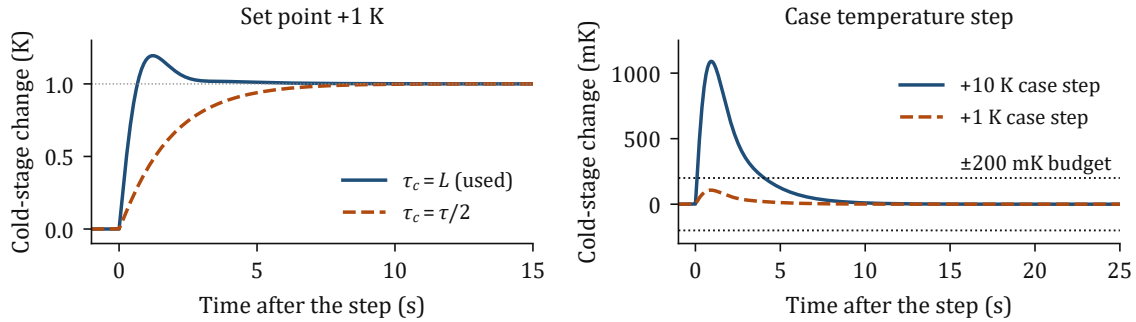


Figure 7. Closed-loop response of the nonlinear model with the PI of Table 3 ($\tau_c = L$). Left: a +1 K set-point step, also for $\tau_c = \tau/2$. Right: a step of the case temperature (heat sink held stiff, $R_{hs} = 0$) of +10 K and +1 K; the dotted lines are ± 200 mK. Simulated.

Figure 7 and Table 3 set the limit on ambient disturbances. A 1 K step of case temperature moves the cold stage 108 mK at the peak, and the largest step held inside ± 200 mK is 1.9 K. A 10 K step reaches 1.09 K and takes 9.9 s to return to ± 10 mK. The case-to-cold-stage gain is 0.91 K per K, carried by the TEC's own back conduction rather than the 100 K/W leak, so 10 K with the loop open would move the cold stage 9.1 K. Real heat sinks move in minutes, hence the ramp term of 4.6 mK for 1 K/min; for faster ambient changes shorten τ_c further or feed forward from a case sensor.

The same cold stage, built as a thermal-electrical analog in LTspice (temperature a voltage, heat a current, the TEC and the PI behavioral sources), reproduces the current-step response to 0.002 mK and the two closed-loop responses to within 1.1 mK (calculation files).

7. A worked example, a checklist, and assumptions and limits

Table 4 is the whole worked example in one place, with the symbols of the calculator and of this note. Enter the inputs in the calculator at jezdangomez.com/calculators/tec-heat-load/ and it prints the same results; everything in sections 3 to 6 follows from them.

Table 4. The worked example, entered as the defaults of the TEC heat load calculator at jezdangomez.com/calculators/tec-heat-load/; the calculator prints these results to these decimals.

Inputs		Inputs, continued		Results		Results, continued	
I_{LD}	0.250 A	I_b	100 μ A	Q_{LD}	0.360 W	Q_h	0.883 W
V_f	1.600 V	R_{th}	10.0 k Ω	Q_{par}	0.200 W	COP	1.74
P_{opt}	40.0 mW	I_{max}	1.800 A	P_{sh}	0.100 mW	$Q_{c, cap}$	3.246 W
T_{set}	25.0 $^{\circ}$ C	V_{max}	3.600 V	Q_c	0.560 W	Load share	17.3 %
T_{amb}	45.0 $^{\circ}$ C	ΔT_{max}	70.0 K	T_{case}	45.00 $^{\circ}$ C	Iterations	1
R_{par}	100 K/W	$T_{h, ref}$	300 K	ΔT	20.00 K	S	12.000 mV/K
R_{hs}	0 K/W			I	0.387 A	R_{TEC}	1.5333 Ω
				I/I_{max}	21.5 %	K_{TEC}	35.49 mW/K
				V	0.833 V	Q_{max}	3.996 W
				P	0.323 W		

Integration checklist

1. Convert the channel tolerance to a chip-temperature budget with the tuning coefficient of your laser at your wavelength (Eq. 1 and 2).
2. Get the chip-to-thermistor resistance from the module datasheet, or measure it: change the drive by a known power at a fixed set point and read the wavelength shift.
3. Compute the gradient at your highest and at end-of-life drive, not only the nominal one.
4. Choose the bias so self-heating is under a tenth of the budget and one ADC count under a twentieth.
5. Trim the set point once, at final drive and mount, against a wavelength reading; record the offset.
6. Size the TEC at the worst-case temperature: capacity at that ΔT , load under about 70 %, ΔT under about 25 K.
7. Iterate the case temperature with the measured heat-sink resistance and check the hot-side heat it must carry.
8. Set the driver current limit below I_{max} , its compliance above V plus margin, and allow reverse current for cold ambients.
9. Route the sense pair away from the TEC pair and the laser current; twist or shield it and filter at the ADC.
10. Run the open-loop step, log the thermistor at 10 Hz or faster until it settles, and fit K_p , τ and L .
11. Compute SIMC gains for $\tau_c = L$; preset the integrator to the present current, add anti-windup, ramp set-point changes.
12. Verify with the final firmware: wavelength against time through an ambient excursion at the hot and cold extremes, against the budget table.

Assumptions and limits

The heat-load and TEC numbers use the ideal thermoelectric equations with the module properties derived from the maximum ratings and held constant at the rated hot-side temperature; they ignore property changes with temperature, contact and spreading resistances other than those entered, radiation and, in the calculator, transients. The dynamic model is one lumped cold-stage node: the chip is not a separate node, so the gap is a static offset. The step test and the closed-loop traces are simulated, not measured. Three entries of the error budget are my assumptions, not

results: the drive-heat variation ($\pm 15\%$), the mount dissipation change ($\pm 20\%$) and the bias reference drift (100 ppm). Wavelength is treated as linear in temperature; mode hops, current tuning and aging are outside the note. These are estimates for early design: confirm them against the TEC manufacturer's data and by measurement before committing a design.

Notes

Symbols. S , R , K TEC Seebeck coefficient (V/K), resistance (Ω), thermal conductance (W/K); Q_c , Q_h heat pumped from the cold side and rejected at the hot side (W); Q_{LD} , Q_{par} , P_{sh} laser heat, parasitic leak, thermistor self-heating; T_c , T_h cold-side and hot-side temperature (K); R_{par} , R_{hs} case-to-cold-stage and case-to-ambient resistance (K/W); k laser tuning coefficient (nm/K); β thermistor constant (K); C , G , τ cold-stage heat capacity (J/K), total conductance (W/K), time constant (s); K_p , L step-test gain (K/A) and dead time (s); K_c , τ_i , τ_c PI gain (A/K), integral time and chosen closed-loop time constant (s).

Basis. Every derived number in this note is computed by the scripts in the calculation files (calc/) and checked against numbers.json before the document is rendered. The TEC and heat-load numbers come from the same equations as the calculator. The step test, the SIMC tuning, the closed-loop traces and the error budget come from thermal_model.py, step_test.py and error_budget.py. The cold-stage model was also built as a thermal-electrical analog in LTspice and run in batch mode; its traces agree with the Python model to 0.002 mK (open loop) and 1.1 mK and 1.0 mK (closed loop, case step and set-point step).

Assumed inputs. The module, the laser operating point and the sensor are an illustrative example (1550 nm DFB, 0.25 A, 25 °C set point, 45 °C case, 10 k Ω NTC with $\beta = 3435$ K, a TEC rated 1.8 A, 3.6 V, 70 K), not a product. The cold-stage heat capacity (0.20 J/K), the chip-to-thermistor resistance (0.25 K/W), the sensor lag (0.3 s) and the three assumed error terms are stated inputs of the example; replace them with measured values for a real design.

References

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