
Section 5

Applying Multiple ADCs and DACs
Control Loops and Converters

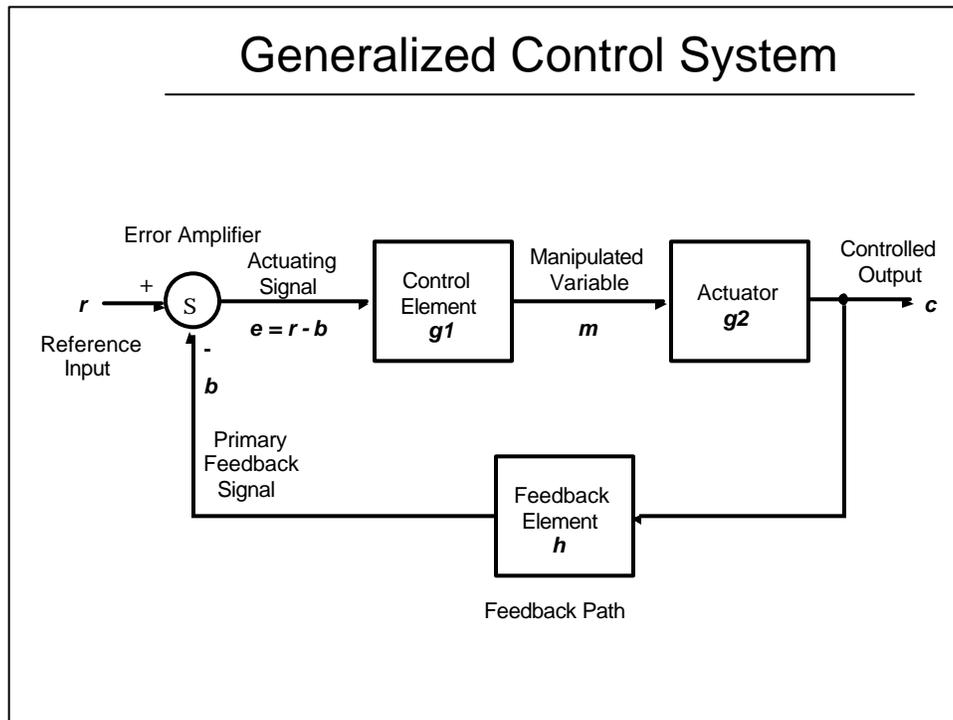
Control Loops and Converters

Control loops use feedback to dictate the performance of a variable, and converters enable the employment of μP , μC , or DSP in the control loop design.

Control loops are feedback loops, and feedback is used to insure that control loop performance is based on stable passive component parameters. The initial accuracy and drift error is very controllable in passive device manufacture, but active devices have poor initial tolerances and are subject to drift especially from temperature. A good control loop holds the controlled parameter at the desired value regardless of load, temperature, or similar ambient changes.

Sometimes the control algorithm is complex, non-linear, or requires software updates, and under these conditions some kind of computer is desirable to implement the algorithm. Computers can't interface with real world variables like temperature, pressure, etc., thus converters are required to complete the analog/digital interface. Analog-to-digital converters (ADC) convert analog voltages/currents into coded binary digital signals compatible with the selected computer. Digital-to-analog converters (DAC) convert the coded binary digital output from the computer into analog signals capable of driving (often with the help of a companion circuit) the actuators.

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The generalized control system includes the parameters and functions defined below.

The actuator, g_2 , is the controlled body; i.e. the motor, actuator, or controlled variable. The control element, g_1 , is the controller or amplifier that acts on the error signal to stimulate the plant. The feedback element, h , is the passive circuit that establishes the ideal closed loop performance of the loop. The reference input, r , commands the system to a specific action or value. The controlled output, c , is the quantity or condition controlled by the system. The actuating signal, e , is the error signal between the reference input and the actual value. The primary feedback signal, b , is a modified form of the controlled output. The manipulated variable, m , is the interface between the control element and the actuator. A disturbance, u , is any undesired input signal that affects the controlled variable. Disturbance inputs may be made to any block depending on the situation. For instance, if one is foolish enough to include noise in the reference signal, then the noise can be modeled as another disturbance input. The error amplifier adds and subtracts its input signals to obtain a composite output signal.

Control System Elements

- ◆ Reference
- ◆ Error amplifier
- ◆ Power driver (Actuator)
- ◆ Transducer
- ◆ Stability

These are the typical elements of an electronic control system, as they relate to the preceding block diagram. We'll look at each of these in a bit more detail, and how they affect accuracy and stability of the overall system.

The Reference

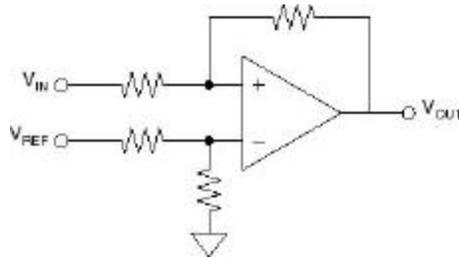
- ◆ Determines the minimum accuracy
- ◆ May contain noise
- ◆ Has purchase and drift tolerances
- ◆ May be buffered because of current limitations
- ◆ Ratio measurements minimize the reference tolerances by common-mode rejection

The reference is summed into the command input of the control system; therefore, a working control system follows the reference at all times. The reference must be very accurate, because the system reproduces and amplifies reference inaccuracies. Also, the reference must be stable and noise free to prevent the system from acting on reference noise or drift.

If the current output capability of the reference is not adequate a current buffer is required. This buffer often takes the form of an op amp configured as a unity gain amplifier (buffer). Filter capacitors are used to decrease reference noise, but the reference or its buffer must be capable of driving capacitive loads without becoming unstable. One method of increasing overall accuracy above the reference accuracy is to use ratiometric measurement methods where all measurements are referred to the same reference.

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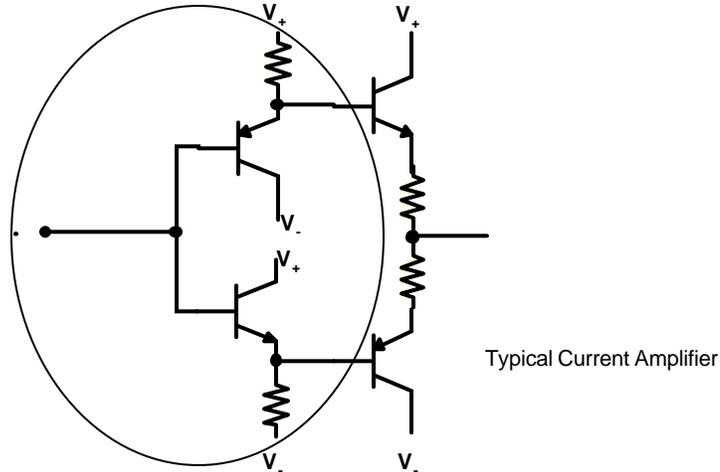
Error Amplifier



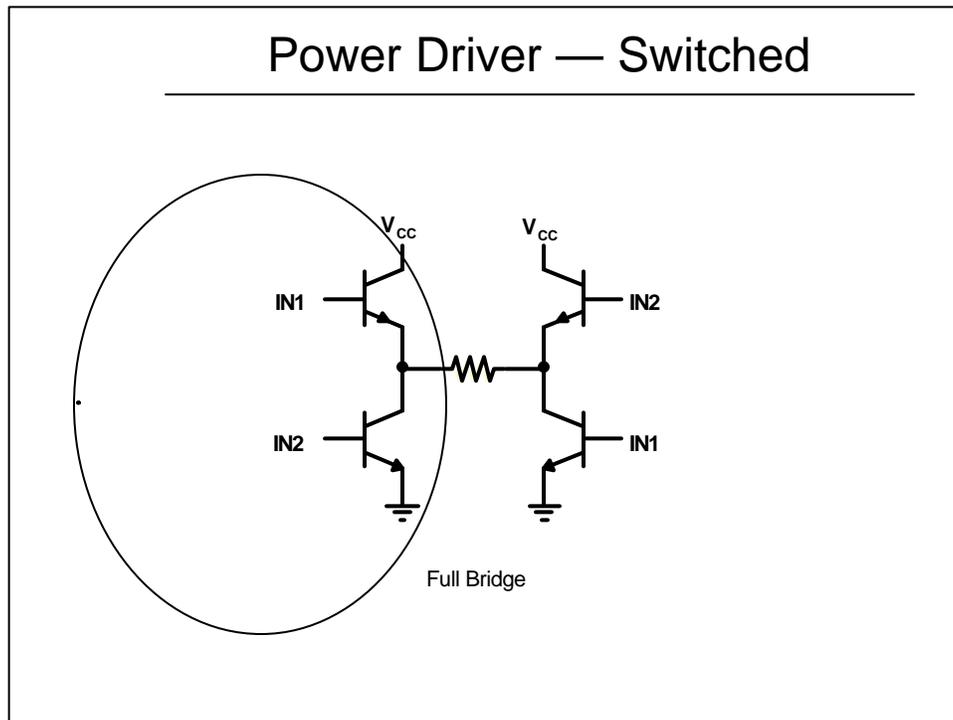
The summer takes any number of input signals and outputs a signal that is the arithmetic sum of the input signals. Theoretically, there is no limit on the number of input signals a summer can handle, but in practice the inputs are usually limited to three or four signals. The inverting input of an op amp is often used as a summing junction that yields an inverting transfer function. This works well in practice, but a non-inverting summer can be constructed from an op amp followed by a unity gain inverter; the non-inverting input becomes the summing junction in this configuration.

Op amp errors, dc and ac, are referred to the input of the op amp because the user determines the stage gain. All op amp error sources have to be considered when designing a summer because these errors are multiplied by the stage gain and injected into the signal path. Precision op amps are used as summers to minimize errors, and often an adjustment is used to eliminate dc errors.

Power Driver — Linear



The power driver is part of the actuator in our generic control system. The traditional way to drive a load is with linear transistors connected in a Darlington configuration. When the transistors are biased normally, the distortion caused by crossover between transistors is almost distortionless, but the bias current causes a large quiescent power drain. The design objective for a linear power driver always is to decrease bias current and distortion, but that is only possible to a small degree. Each transistor in the Darlington is on at zero volts, thus the crossover from plus to minus is continuous.



Switched power drivers dissipate low power during their “on” state because there is little voltage across the driver. They dissipate high power when their output is in the linear state (half the supply voltage), but they pass through the linear state quickly, so overall they dissipate very low power compared to the load power. The price paid for low power dissipation is distortion, switching noise, EMI generation and circuit complexity.

The output voltage of a switched power driver is quasi-digital, and when it is filtered in the load it reproduces the analog signal with some distortion. Also, some degree of switching noise always contaminates the power rails. Fast voltage/current switching produces EMI, but this is not a problem with late generation ICs because advanced techniques reduce the EMI to acceptable levels.

Transducer

- ◆ Must supply bias or excitation V or I as specified by the data sheet
- ◆ Must be operated within a specified ambient to obtain data sheet performance
- ◆ Often require linearity compensation
- ◆ Must characterize to verify data sheet
- ◆ May need conditioning

Transducers often require a bias or excitation voltage or current. The bias or excitation V/I must meet all of the data sheet requirements and specifications to maintain the transducer accuracy. Noise or drift on the bias or excitation V/I is reflected in the transducer output as noise and drift. Meeting the data sheet specifications requires that transducers are operated within the ambient temperature range specified on the transducer data sheet.

Some transducers have non-linear transfer functions, so the conditioning circuit or the processor must linearize them before system use. Special classes of transducers like thermistors and thermocouples are widely used, and conditioning circuits that incorporate the linearization are available. The transducer must always be conditioned so that it has the correct span, offset voltage, and output impedance to fully utilize the converter. Special transducers made for specific applications should be characterized to insure that they meet the data sheet promises when operated under data sheet conditions.

Stability

- ◆ Measure stability by overshoot in time domain or peaking in frequency domain
- ◆ Peaking and overshoot occur at lower frequencies than oscillation
- ◆ Circuits require compensation for layout and cabling
- ◆ Transducers and actuators require compensation

Stability is often thought of in terms of oscillation, but stability has an effect on the system long before oscillation occurs. Peaking of the frequency domain transfer function occurs at lower frequencies than oscillation does, and peaking causes distortion because high frequencies are emphasized. Also, overshoot in a time domain function occurs at lower frequencies than oscillation does, and overshoot causes distortion because high frequencies are emphasized.

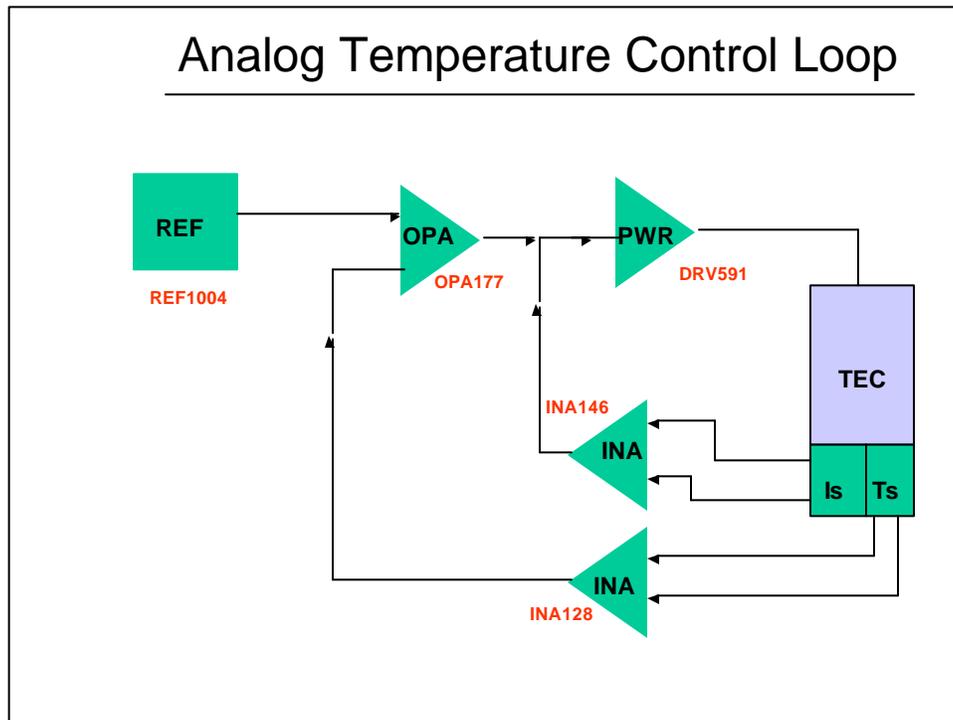
Instability is usually introduced by stray layout capacitance that forms a pole in the circuit's feedback loop. Stability is usually achieved through some form of compensation by strategically adding capacitors that form zeros in the feedback loop. Ideally, the zeros cancel the poles caused by the stray capacitance, and the affect of the poles does not come into play until higher frequencies where the gain has decreased considerably. Transducers and actuators have poles in their transfer functions, thus they have a tendency to contribute to instability. Transducer and actuator poles must be compensated to obtain the maximum frequency response.

Applications of Control Loops

- ◆ Constant speed—printer head
- ◆ Position—inertial navigation system
- ◆ Flow control—mixing fluids, filling tanks
- ◆ Temperature control—semiconductors processing, baking ovens, ambient temperature
- ◆ Voltage/current control—power supplies
- ◆ Transducer enhancement—low output Z

Control loops are widely used in industry. We readily recognize that a printer head must move at constant velocity for the printing to be uniform, thus understand that a printer velocity is controlled by a control loop. The new kitchen mixer is not recognized as containing a control loop, but the ever decreasing cost of ICs has made this possible. Listen to the mixer the next time you are in the kitchen. When the batter gets stiffer and dryer the motor indicates that it is working harder by a complaining sound, and if the mixer speed remains constant it contains a control loop.

Another popular application of control loops is temperature control. Older residential temperature controllers were on/off thermostats, but newer temperature control loops vary the air conditioning compressor speed to change the temperature of the conditioned air. Varying the compressor motor speed is more cost effective and it yields more comfort.



The thermoelectric cooler (TEC) is used to keep a laser diode at constant temperature. The primary control loop is the TEC thermistor, whose output voltage (T_s) is buffered by the instrumentation amplifier (INA). The INA conditions and linearizes the thermistor signal, and applies the result to the op amp and then to the power amplifier. The TEC current (I_s) is applied to a different INA that removes the common-mode voltage present on the current signal before applying it to the power amplifier; this acts as a protection feature rather than the controlled variable. This is a complete analog control loop, and it does not require any help from the system or the processor, but it does not communicate any information to the processor. Also, the reference diode has to be changed to obtain a different set point.

Pros and Cons of Analog Control

◆ Advantages

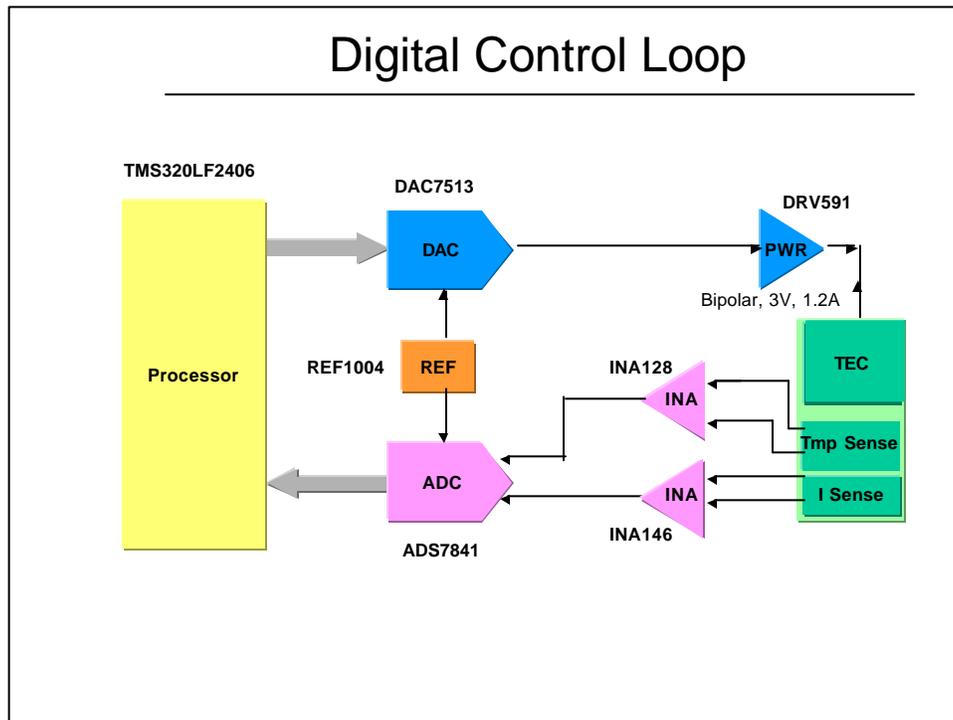
- Easy to implement simple control function (such as PID control)
- No software development

◆ Disadvantages

- Dependence on component values
 - ◆ Temperature drift
 - ◆ Aging effects
- Fixed Control Function
 - ◆ Hard to do complex control, like adaptive or optimizing
- No communication with central computer
 - ◆ No monitoring of parameters
 - ◆ No alarms
- Manual initial setting

The advantages of an analog control loop are simplicity, cost, easy implementations and no software development. The disadvantages of an analog control loop are drift caused by ambient changes and life, although digital control loops are sensitive to drift to a lesser extent. Another disadvantage is lack of flexibility because software programming is not available, and because no data goes into the computer where there are status signals available for alarms, etc.

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Notice that the TEC module configuration has not changed from the analog control loop. The thermistor and current sense signals are still buffered and conditioned by two INAs, and their outputs are connected to the ADC input. The ADC multiplexes the inputs into the converter, compares the signal to a reference voltage, digitizes the result and sends it to the processor where the data is modified by a control algorithm and stored in memory. The control algorithm and the INA are capable of linearizing the thermistor signal, so the choice is determined by the designer. The processor commands the control loop through the DAC and power amplifier. The digital loop is more complex, but it receives the thermistor and current data, enabling it to store or report status. Changing the set point in a digital system is easy; send a new set point command to the processor and the system responds to it on the next processor cycle.

This control problem could also be addressed by using a microcontroller or DSP. It could be done as shown here, as a hybrid analog/digital loop, or it is conceivable to use a C24X DSP, driving FETs with the PWM outputs, and have the whole solution in code.

Pros and Cons of Digital Control

◆ Advantages

- Communication with the host
 - ◆ Can monitor status of control loop
 - ◆ Alarm
- Programmable setpoint
- More complex control functions possible/practical

◆ Disadvantages

- Software development necessary

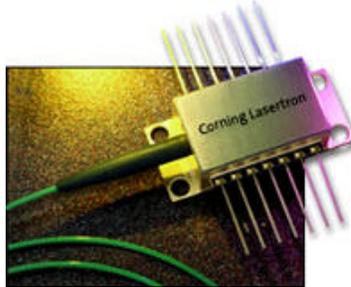
The digital control system allows the processor to monitor the status of expensive components and assure that the system is operating within specified parameters. If it's not operating properly, the processor can set alarm signals and shut the system down safely.

More complex control algorithms can be used as well in the digital system, and since all the setpoints are controlled by the processor, the system can adapt or be optimized as required.

The downside to this approach, though, is that someone has to develop the software to run it all!

Example

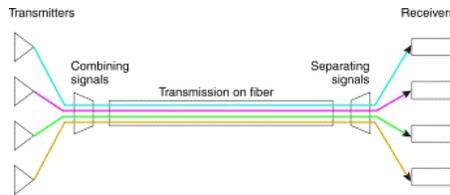
Laser Diode Control for DWDM Systems



Now let's look at an example of a system where we can use data converters in control loops. Optical networking is becoming a more important networking option, and it presents some interesting control system challenges. The particular challenge we'll look at today is controlling the laser diode in a DWDM system.

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DWDM



- ◆ WDM: uses each wavelength as a separate channel for different types of traffic (SONET/SDH, ATM, TDM voice, video, data) at different bit rates.
- ◆ DWDM-Dense WDM
- ◆ Transmission and signal amplification uses tunable laser diode modules.

DWDM stands for Dense Wavelength Division Multiplexing – this is the same concept as frequency division multiplexing that is used to send many channels down your cable TV line. In this case, the “cable” is actually an optical fiber, and the many different channels of data are multiplexed onto different optical frequencies, or as more commonly referred to when discussing light, wavelengths. In order to generate the many wavelengths of light, tunable lasers are used.

As the optical signals travel down the fiber, their optical power needs to be maintained. This is done in a fashion similar to using repeaters in radio; periodically along the fiber, the signals are re-amplified to maintain the optimum optical power. This amplification takes place in the optical domain, using an Erbium-Doped Fiber Amplifier, or EDFA. We’ll examine what makes up an EDFA shortly.

Nanometers and Gigahertz

- ◆ What's the correlation?
- ◆ DWDM center lambda is at 1545 nm or 129,450 GHz
- ◆ Total BW available on a fiber is roughly 50 nm or 4,000 GHz
- ◆ 50-GHz Channel = 0.6 nm

SYSTEM	CENTER	CHANNEL	TOLERANCE	CHANNEL/CARRIER	DRIFT
RF	450MHz	15kHz	±0.001MHz	1/30000	±2ppm
OPTICAL	129THz	50GHz	±0.5GHz	1/2500	±4ppm

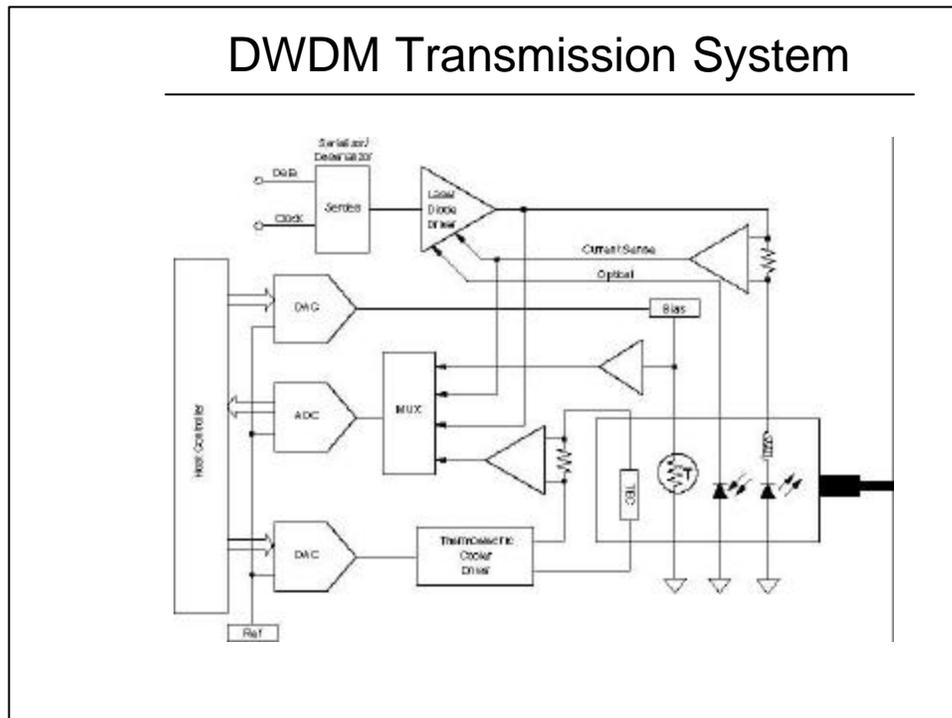
Before going much further, let's look at the correlation between bandwidth and wavelength. DWDM's center frequency is at 1545nm or 129,450GHz. The total bandwidth available is about 50nm or 4,000GHz (1530 to 1560nm). A 50GHz channel then only takes up 0.6nm.

Now, to draw a quick analogy, let's compare an RF channel to an optical channel. Consider an RF channel with a 450MHz ± 0.001MHz carrier with a 15kHz channel. This is a basic RF channel. If the carrier stays within 1kHz of the set frequency, all is well. Typical deviation or bandwidth in this band is 15kHz. With the optical channel, you have a 129,000GHz ± 0.5GHz carrier with a 50GHz channel.

Compare now the ratios of the channel to the carrier. In the RF system, channel/carrier = 1/30,000; in the optical system, channel/carrier = 1/2500. The optical channel has 10x deeper modulation. That's OK though, because the FCC really doesn't enforce interference to the color red.

RF Drift/Carrier = 1/450K (±2ppm); Optical Drift/Carrier = 1/260K (±4ppm). Note for future reference that it takes a PLL loop to hold the RF carrier to this spec. One challenge for our control system is maintaining stability to within ±4ppm.

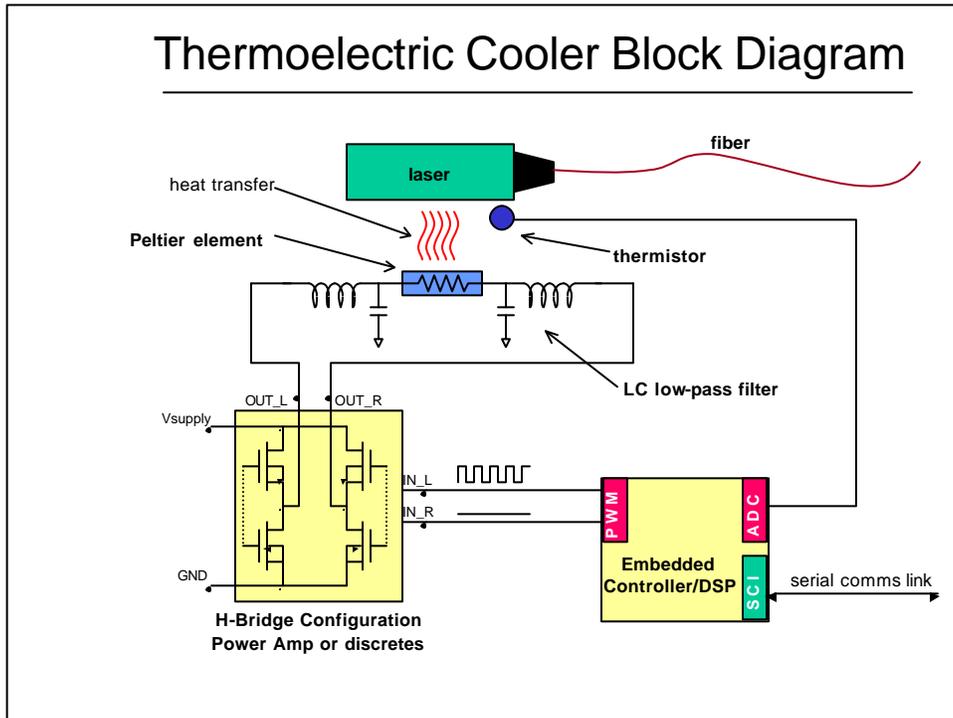
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The tunable laser diode modules can be seen at the right of this slide. The module consists of a laser diode and a thermoelectric cooler. The cooler acts to keep the laser diode at the same temperature, regardless of how much power is being used in the diode. This is critical as the laser's wavelength will change with changes in temperature. An additional diode, used to monitor the optical power output from the laser diode, is included, and is often fabricated on the back facet of the laser; hence it is sometimes referred to as the back facet diode.

The control system around this laser diode module is hinted at here: a means of controlling laser diode current is needed, as well as a temperature control loop which controls the thermoelectric cooler. Various critical parameters of the system are monitored and controlled by analog-to-digital (ADC) and digital-to-analog (DAC) converters.

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The thermoelectric cooler consists of a Peltier element in close contact with the laser diode. A thermistor is provided to monitor the temperature at the laser diode. The Peltier element is then driven by some kind of power driver which monitors the thermistor and causes the driver to source or sink current through the Peltier element to maintain a constant temperature.

Optical Network Problem

- ◆ Control current through a laser diode for optimal power output, while maintaining temperature within $\pm 0.1^\circ\text{C}$ to control laser's output wavelength

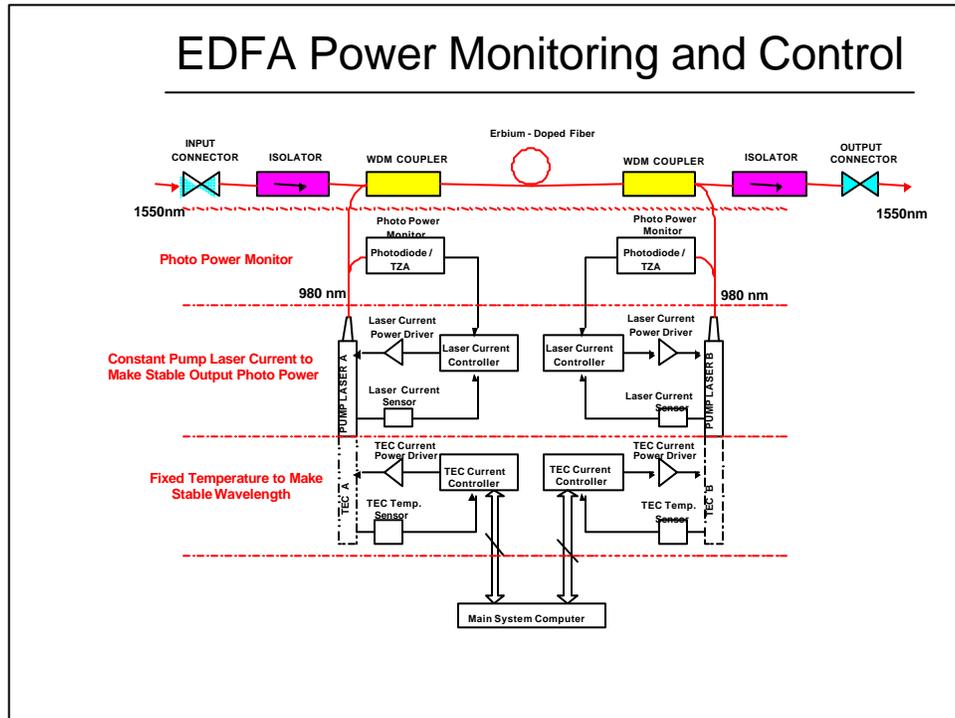
- ◆ Also:
 - Monitor laser current
 - Monitor laser temperature
 - Monitor TEC voltage and current

So now that we have the basics of the problem, let's restate it: we must control current through a laser diode to provide optimal optical power output, while maintaining tight control of the laser's temperature so that we can keep the laser diode on the desired wavelength.

This means controlling the temperature within $\pm 0.1^\circ\text{C}$, while driving the laser diode with as much current as it can handle, all the while monitoring the laser current, the laser temperature, and the TEC voltage and current.

This example was chosen because it includes both analog and digital techniques for the control and monitoring of the various system parameters, and different control approaches are possible. Two different power driver approaches will also be shown. A solution to a key accuracy problem will be presented which uses a unique approach to using the system reference as well.

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Here's a more detailed view of an EDFA. The optical power monitors can be seen near the top of the diagram. The pump lasers must have a constant current flow to them, in order to keep the optical power output constant and to keep the laser on wavelength.

The temperature of the laser diode is critical in maintaining a constant wavelength, so it must be controlled. This can be challenging, because as you drive significant current into the laser diode to provide the power desired, the temperature cannot change. These systems address this problem by using a Thermo-Electric Cooler (TEC) inside the laser diode module. The cooling or heating of the laser diode is then controlled by another current which flows through the TEC. This current, as well as the pump laser diode current, must be precisely monitored and controlled.

Laser Diode

- ◆ 980-nm Pump Laser
 - ± 5 -nm initial accuracy
 - Must not drift more than ± 0.5 nm

A typical 980-nm pump laser may only have an initial wavelength accuracy of ± 5 nm; when in operation, however, they must remain within ± 0.5 nm over time and temperature to maintain acceptable noise levels in the EDFA.

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Laser Specifications

Parameter	Conditions	Min	Typ	Max	Units
Center Wavelength	20mW to P_k at 25°C, -20dB Reference Level	970		986	nm
Spectral Width	20mW to P_k at 25°C, -20dB Reference Level		0.3	1	nm
Spectral Stability vs. Temperature	$T_{\text{submount}} = 25^\circ\text{C}$, $T_{\text{grating}} 0 \text{ to } 75^\circ\text{C}$		0.01	0.02	nm/ °C
Operating Voltage	$P_o = 250\text{mW}$		2.04	2.30	V
Operating Current	$P_o = 250\text{mW}$		460	500	mA

The laser module for our example is a 975-nm pump laser, with 250-mW output power. This particular laser module is not tunable, but we will design our system so that tunable lasers and pump lasers at other wavelengths may be used in the future.

Laser modules require drive currents in the range from 300 mA up to 3 A. The particular laser for our example requires a minimum threshold current of 35 mA to operate, and can be driven up to 500 mA when achieving maximum power output.

All laser modules' output wavelengths are temperature dependent. Modern lasers, like the one we will use, achieve ± 0.02 nm/°C temperature dependence. This is a great improvement over just a year ago, when most lasers had a 1 nm/°C temperature coefficient.

For system stability, note that maintaining $\pm 0.1^\circ\text{C}$ temperature stability with the newer laser still may result in a change of 0.002 nm out of the 975-nm center wavelength. This is a change of ± 2 ppm. So even with the great advances made in the lasers over the past year, temperature control is still a very important part of the optical system.

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Back Facet Monitor Specifications

- ◆ Photodiode on back facet of laser diode
- ◆ Used for monitoring optical power
- ◆ May also be used to monitor output wavelength

Parameter	Conditions	Min	Typ	Max	Units
Photodetector Responsivity	@ P _o	2	7	30	μA/mW
Photodetector Capacitance				10	pF
Tracking Error	@ P _o	-20	0	20	%
Tracking Ratio	0.1 P _o to P _o	0	8	30	%

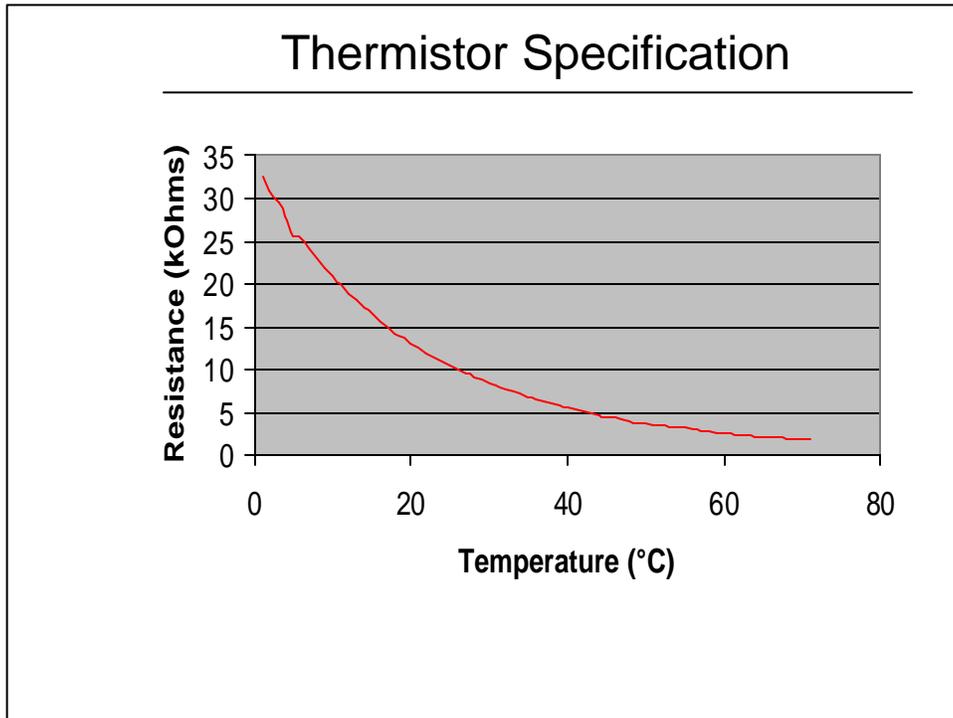
The diode formed on the back facet of the laser diode can be used as a photodiode to monitor the optical power output. In our laser module, the responsivity of this diode is typically 7 μA/mW, but can be as low as 2 μA/mW and as high as 30 μA/mW.

With 250 mW, $I_{bfm} = (30 \mu\text{A/mW})(250 \text{ mW}) = 7.5 \text{ mA}$ max. typical 7 μA/mW gives 1.75 mA typical.

The tracking error specification tells us the change in responsivity over temperature. This won't factor in too much, as we will be maintaining the laser at a constant temperature (±0.1°C) using a TEC.

Tracking ratio, however, is a specification to which we need to pay attention. It is the linearity of measured power versus the current output from the diode. At first glance, this looks terrible: the current output for a given optical power may vary by as much as 30%! In reality, that's true only at very low powers. At close to the rated power for the laser, the tracking ratio actually is closer to something like 1%.

Note that the wide variability of responsivity means that our system must be designed to handle a dynamic range which will accommodate the lowest as well as highest responsivity.



The thermistor used in the laser module has a negative temperature coefficient. The nominal value of the thermistor is $10\text{K} \pm 500$ ohms, at 25°C . Like all thermistors, its response is nonlinear over a wide range of temperature.

Since the thermistor is our transducer for measuring temperature, and we need to measure and control temperature within 0.01°C , we must linearize this transducer. Fortunately, we know the characteristic of this thermistor, so we can easily take the nonlinearity into account. This, unfortunately, is not the case with the back facet monitor diode—we don't know the nature of its nonlinearity.

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Thermo Electric Cooler Specification

Parameter	Conditions	Min	Typ	Max	Units
TEC Cooling Capacity	$T_{\text{case}} = 75^{\circ}\text{C}$			50	$^{\circ}\text{C}$
TEC Current	$\Delta T = 50^{\circ}\text{C}$, at P_o , $P_o > 150\text{mW}$		1.1	1.8	A
TEC Voltage	$\Delta T = 50^{\circ}\text{C}$, at P_o , $P_o > 150\text{mW}$		2.5	3.4	V
TEC Power	$\Delta T = 50^{\circ}\text{C}$, at P_o , $P_o > 150\text{mW}$			5	W

The thermoelectric cooler in our example laser module can draw up to 1.8 A when the difference between one side of the cooler and the other side is 50°C . So we have a challenge in designing a driver for that kind of current.

We also have to make sure that the TEC does not have more than 3.4 V applied across it, as higher voltages will damage the element.

Note that there are no accuracy specifications for the TEC— this is a device which is intended to be used in a closed-loop control system. The accuracy of the temperature control will depend upon the temperature measurement through the thermistor, and the control of the current through the TEC.

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Summary – Specs and Control Problem

Parameter	Control Limit	Depends Upon	Laser Spec	Max Spec	Design Goal
Laser Wavelength	$\pm 0.5\text{nm}$	Temperature	$1\text{nm}/^\circ\text{C}$	$\pm 0.5^\circ\text{C}$	$\pm 0.1^\circ\text{C}$
Laser Power	$\pm 0.5\text{dB}$	Current	$0.5\text{mW}/\text{mA}$	$2\text{mA}/500\text{mA}$ (0.8%)	0.5%

So the problem breaks down into two control problems. The first problem is to control the temperature of the laser diode. In our pump laser example, this requirement isn't nearly as demanding as it would be if this were a tunable signal laser. Remember, the signal laser wavelength needs to be controlled to ± 4 ppm. In the pump laser case, the wavelength needs to be controlled to within ± 0.5 nm of the initial wavelength. This means that only drift is a problem for us, not the initial value. As long as we're close to the 25°C that the laser wants to operate at, the pump will still work. But its stability is most critical.

Since many lasers have a $1\text{-nm}/^\circ\text{C}$ tempco, this means that the temperature should be controlled to within $\pm 0.5^\circ\text{C}$ maximum. However, since drift appears as noise in the amplifier, any change will degrade the optical signal-to-noise ratio. So our design goal is to achieve $\pm 0.1^\circ\text{C}$ drift to minimize noise. This will also give us ample room for drift due to amplifier aging. (Note that the actual laser we're using in our example is much more forgiving of temperature change, with a much lower tempco than $1\text{ nm}/^\circ\text{C}$. While this is nice, we're still going to control within $\pm 0.1^\circ\text{C}$, to achieve maximum SNR).

The second control problem is that of controlling the current through the laser diode. In real EDFAs, a separate very accurate optical power monitor is used. In our system, we'll use the back facet diode as a rough estimate of the optical power. It's a rough estimate, because the initial accuracy of the back facet monitor is only $\pm 20\%$, and at any given power level, only stable within $\pm 1\%$. Our actual control, however, is not dependent upon optical

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power, but on a current level that we specify and measure. The accuracy of this measurement is affected by the reference initial tolerance and drift, and the initial tolerance and drift on the resistor we'll use to sense the current, as well as errors from amplifiers in our system. However, the sensitivity of the laser diode to current is approximately 0.5 mW/mA in its linear region. If we can control the optical power to within 1 mW, we can achieve 0.5-dB accuracy. So we must be able to control the current to within 2 mA out of 500 mA, or 0.8%. We'll shoot for 0.5% in our design, in order to allow for aging drifts and such.

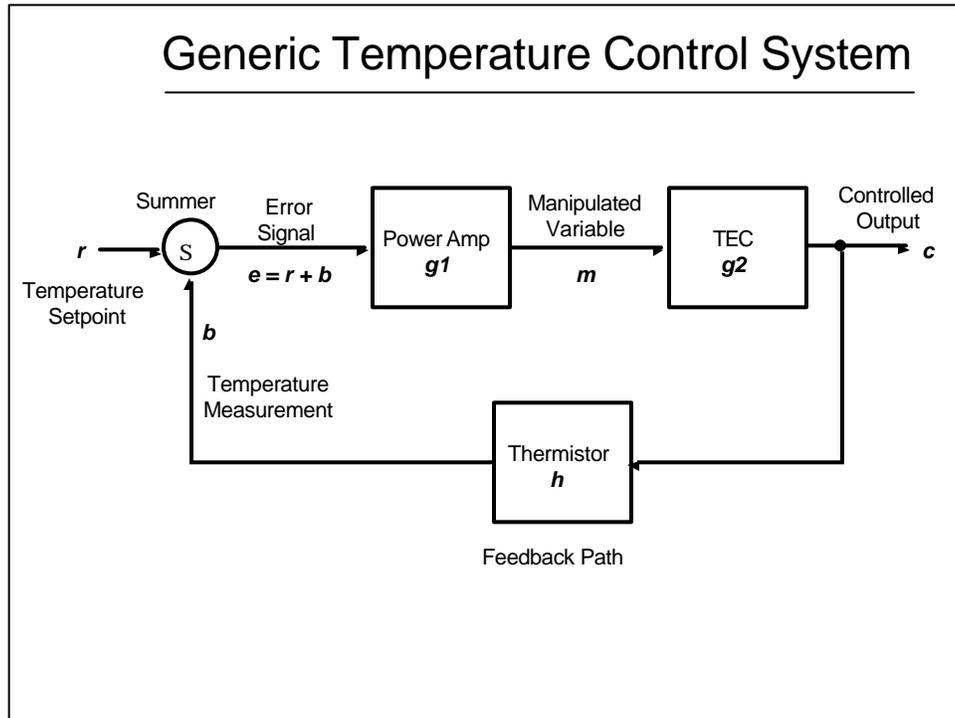
Monitor Specification

- ◆ Management Information Base
 - Set of parameters monitored per network component
 - For EDFA
 - ◆ Number of channels
 - ◆ Wavelength
 - ◆ Optical SNR
 - ◆ Pump temperature
 - ◆ Pump voltage
 - ◆ Pump status
 - For QoS factors – fault detection

Since these optical networking components are part of a large system, a standard has been established for monitoring and reporting the status of each network component. This is called the Management Information Base, and for the EDFA, the parameters listed on this slide must be able to be reported back to a central computer which monitors these parameters. This is done to insure quality of service (QoS) and to detect faults in the system.

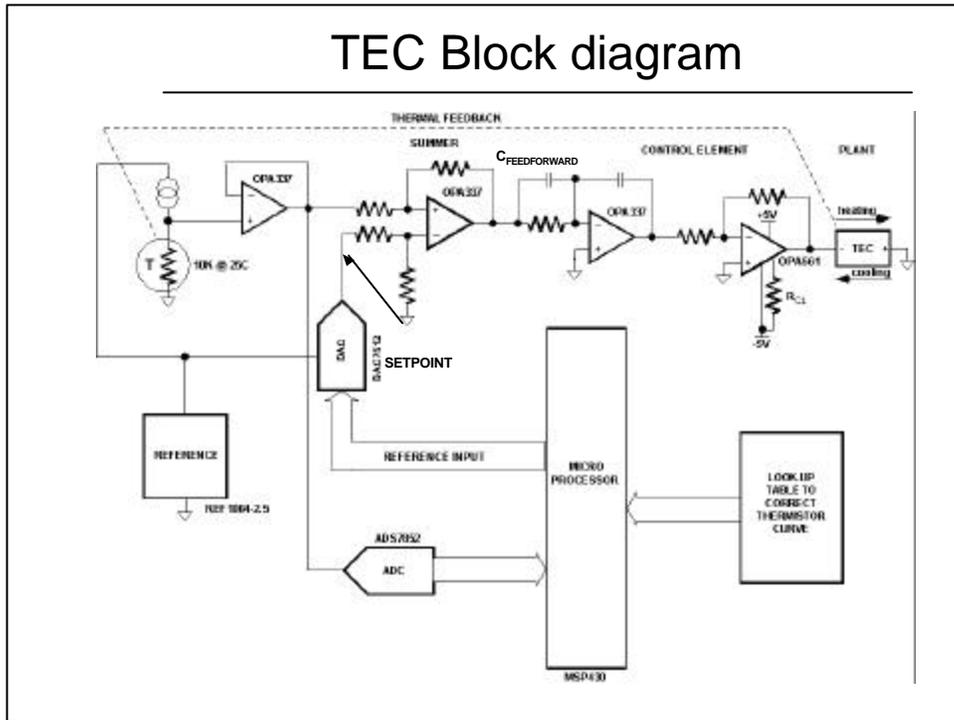
As can be seen, our EDFA must be able to measure the optical SNR as well as voltages and temperatures.

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for Industrial Applications Seminar



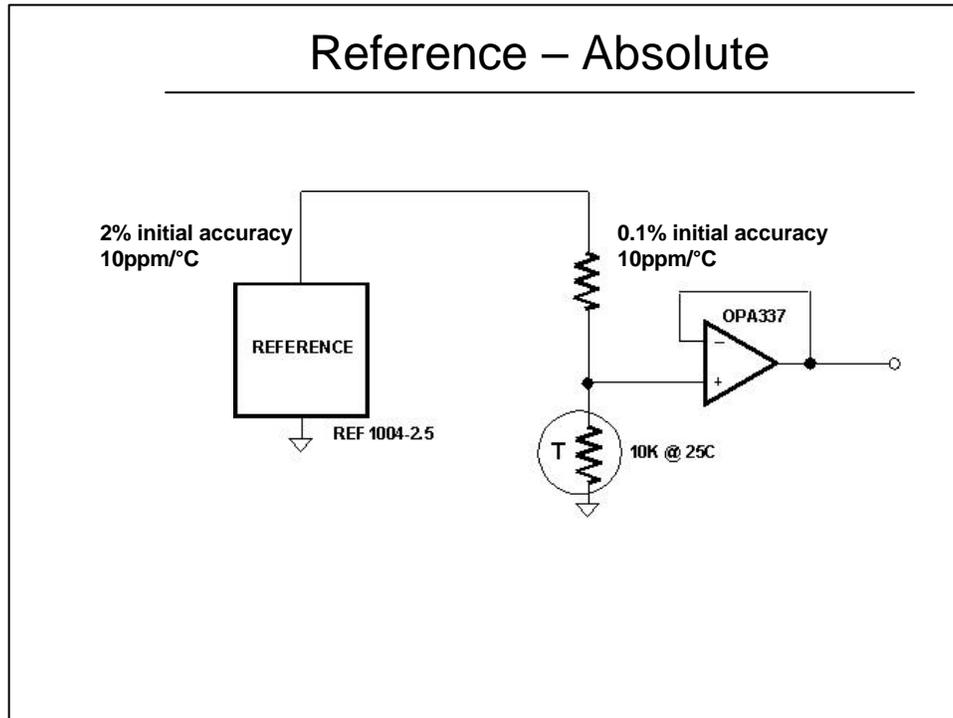
Let's first look at the temperature control problem: maintaining a temperature around a setpoint within $\pm 0.1^\circ\text{C}$. Our generic control system block diagram is shown here, with the details of our system. The temperature must be measured, and this is supplied to a summer (actually a difference) amplifier which will find the error signal between the temperature setpoint and the actual measured temperature. This error signal will then be supplied to a power amplifier to drive the large currents required through the thermoelectric cooler (TEC) to effect a change in temperature.

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This is a schematic diagram of the system that implements the block diagram we just looked at. We'll go through each part of this circuit in the slides that follow, and see how to choose the components used.

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One way of measuring temperature is to use a reference voltage, a resistor and a thermistor connected as shown. As the thermistor's value changes with temperature, the voltage buffered by the op amp will vary, and this can be used as a temperature indicator. Of course, this result would have to be linearized to account for the nonlinear response of the thermistor.

Even so, let's look at how accurate this measurement might be, particularly if we intend to use it as part of our control system. Since the measured temperature is subtracted from the desired temperature setpoint, we must know the exact voltage corresponding to an exact temperature if we hope to be able to set the system to an exact temperature.

The reference voltage has an initial 2% tolerance; the resistor has a 0.1% tolerance, and the thermistor value has an initial tolerance of 5%. So initially, our system is accurate to within 7.1%. Over temperature, the reference and the resistor both drift by 10 ppm/°C. So, while the thermistor may stay near the 25°C we desire, the reference and resistor may be subjected to temperatures down to 0°C and up to 75°C. This 75°C span would result in a drift over temperature of 0.075%.

Thus, our temperature measurement accuracy over the ambient temperature range of our system is 7.175% - about 1.8°C at 25°C, 5.3°C at 75°C.

DAC Function

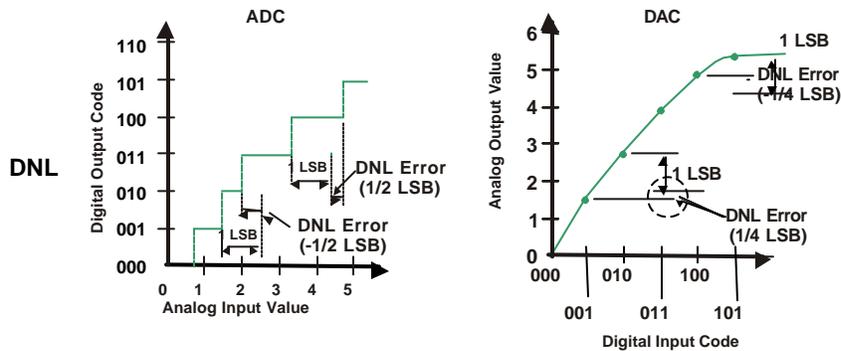
- ◆ Control temperature setpoint
- ◆ Assume 100 μ A flows through the thermistor
- ◆ From thermistor curve, 1°C setpoint difference is ~ 6 mV
- ◆ Require LSB < 6 mV for 1°C control
- ◆ Prefer 0.1°C control = 12-bit DAC

The DAC in our TEC control loop must be able to set the temperature setpoint in at least 1°C increments. If we look at the thermistor curve, and assume that 100 μ A flows through the thermistor, we can find the smallest change in voltage output from the thermistor that would correspond to a 1°C change in temperature. In our example, this turns out to be about 6 mV.

If the DAC output range is 2.5 V, then the minimum resolution for the DAC is 9 bits. Ideally, though, we'd like to be able to change the control for the temperature in 0.1°C increments. This requires a 12-bit D/A converter.

DNL, INL, Monotonicity

- ◆ DNL: Steps same size: <0.5 LSB
- ◆ Monotonicity: required
- ◆ INL: with enough resolution, you achieve setpoint, so can tolerate higher INL



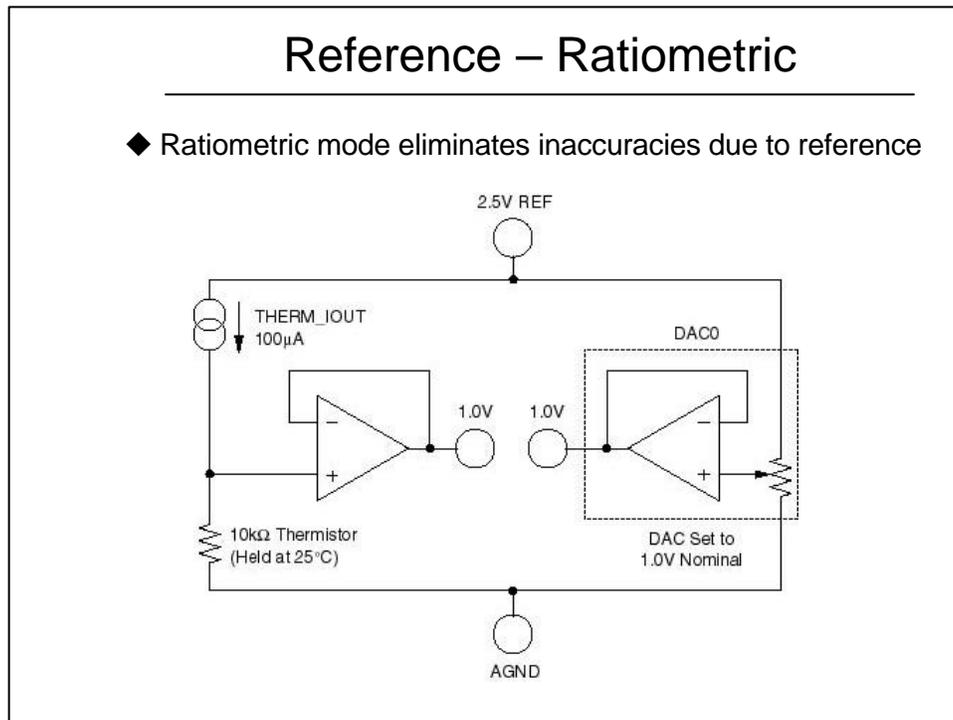
A DAC has three important specifications to consider when choosing a DAC for a particular application. In control loops, the converter's differential nonlinearity (DNL) is important since it is a measure of how close to the same size each step of the output is to each other. For control purposes, we'd like all the steps to be the same size, so the result is predictable.

The integral nonlinearity (INL) is a measure of the end-to-end linearity of the converter's output—in other words, where you end up as you go up and down the output range of the converter. In a control loop, this doesn't matter as much as in other applications, since you are constantly monitoring the output, and will increase or decrease it based upon that feedback.

This is where monotonicity plays a big role. Monotonicity is a specification for a DAC which says that for an increasing input code, the output voltage will always increase. This is very important in control loop situations—imagine if the DAC, which was controlling a loop, was not monotonic. As you want the output to increase, you send a larger code to the DAC. The output increases; you send the next larger code, and then the output decreases. Your feedback tells you now that you must increase the code again, and maybe things will go to where they need to be, and maybe not. This can cause “chattering” or oscillation around a desired output, and is disastrous for control system applications.

Reference – Ratiometric

- ◆ Ratiometric mode eliminates inaccuracies due to reference



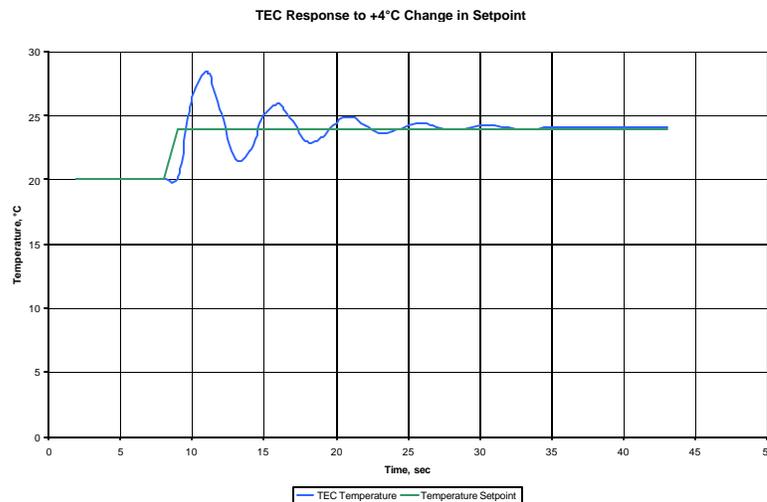
You may have noticed that we have a potential problem: our DAC has a resolution that's equivalent to 0.1°C, but it requires a reference voltage. As seen from our previous example with the thermistor, that reference will have an initial tolerance of 2%, and a drift of 10ppm/°C. How can we eliminate this error?

The answer is simple: use the same reference for both the DAC and the thermistor. If the current flowing through the thermistor is proportional to the reference voltage, and the temperature setpoint of our control system is also proportional to the reference voltage, then, in essence, what we are attempting to do in our control system is cause the voltage across the thermistor to equal the voltage out of the DAC. This bridge arrangement, as shown here, works extremely well as the control loop is geared toward applications where two voltages must balance.

By using the reference in this ratiometric mode, the absolute value of the reference doesn't matter; moreover, drifts over time and temperature won't affect the temperature control loop at all.

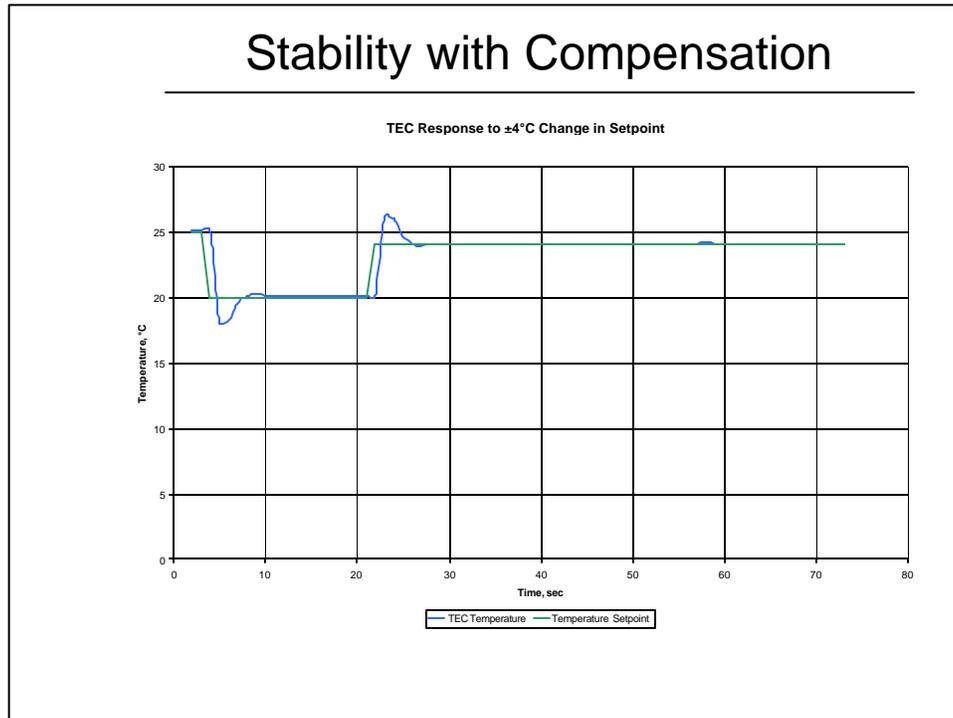
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Stability – Need for Compensation



As we change the temperature setpoint, the loop will attempt to force the temperature to the setpoint. If the error amplifier/integrator is not compensated properly, the loop will overshoot and ring for quite some time. As seen here, a 4°C change in setpoint results in the loop taking over 30 seconds to stabilize.

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Adding a feedforward capacitor ($C_{\text{FEEDFORWARD}}$) to the integrator greatly reduces the overshoot and the time needed for the loop to stabilize. This plot shows a $1\text{-}\mu\text{F}$ capacitor used as the feedforward capacitor; the system is still a bit underdamped. Note that the response time has reduced to about 5 seconds.

Compensating control loops and operational amplifier circuits is a subject almost unto itself. More information on this topic can be found in these references:

Op Amps for Everyone:

<http://www-s.ti.com/sc/psheets/slod006a/slod006a.pdf>

Feedback Plots Define Op Amp AC Performance:

<http://www-s.ti.com/sc/psheets/sboa015/sboa015.pdf>

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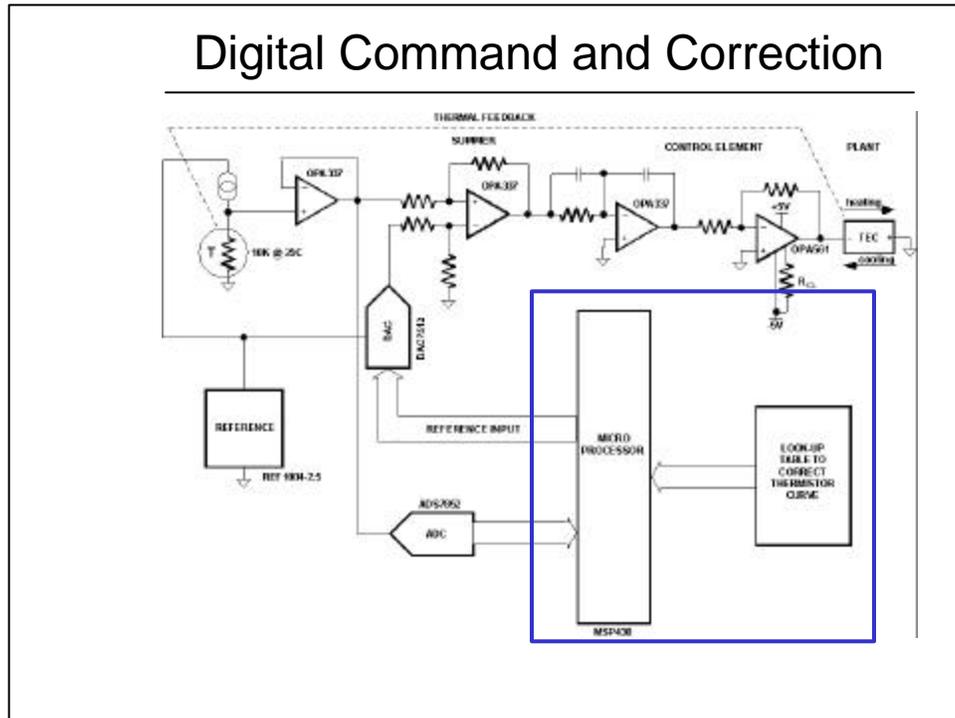
ADC Selection

Device	Resolution (Bits)	Sample Rate (kSPS)	Analog Inputs	DNL (\pm LSB)	INL (\pm LSB)	NMC (Bits)	SINAD (dB)	Package
ADS7824	12	40	4	0.5	0.5	12	72	DIP, SOIC
TLC2543	12	66	11	1	1	12	NA	DIP, SOIC, PLCC, SSOP
ADS7844	12	200	8	1	1	12	72	SSOP
TLV2544	12	200	4	1	1	12	69	SOIC, TSSOP
ADS7852	12	500	8	1	1	12	71	TQFP
ADS7864	12	500	6	1	1	12	70	TQFP

In the control loop we've been looking at, the actual control happens in the analog domain. The ADC is not a part of the actual control, but it does play an important role in the monitoring of the temperature for the Management Information Base.

Since we need to resolve 0.1°C, and perhaps better, we'll stick with a 12-bit converter for the ADC. The reference for the ADC should be the same as that of the DAC and the thermistor, so that the entire system is ratiometric.

Because of the thermal mass of the laser diode and the TEC, the ADC conversion time does not need to be particularly fast. Note that if the control loop were purely digital, the ADC's conversion time would be quite important, as the time it took to do a conversion would introduce latency into the feedback. In a temperature control application, this time may not be problematic, but keep this in mind as we consider other control loop applications.



So far, we've not considered how to linearize the thermistor; we've only noted that it needs to be done. Since our control setpoint is the output of a DAC, that setpoint must be controlled by a microprocessor. Referring back to our schematic for this control loop, you can see that the microprocessor has lookup table to linearize the thermistor. By knowing the characteristic of the thermistor, and the excitation we're providing it, the microprocessor can calculate the voltage that corresponds to a certain temperature.

Actually, the calculation will find a code which is a ratio of the output to full-scale; this code is what is sent to the DAC. Remember, since our converters and the thermistor are all using the same reference, the absolute voltage doesn't matter; only the ratio to full-scale matters.

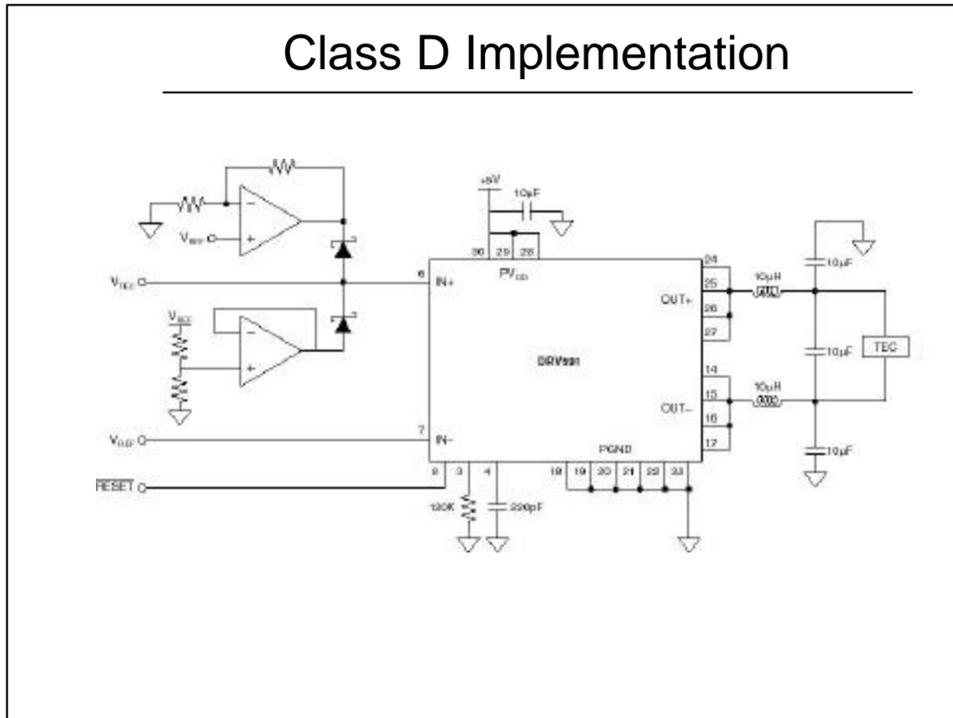
Power Control

- ◆ How to Drive the TEC?
 - Linear Power Amplifier
 - ◆ Low noise
 - ◆ Good efficiency if TEC, power supplies can be similar
 - Class D
 - ◆ Better efficiency
 - ◆ Less power (heat) dissipated in driver
 - ◆ Higher noise, but manageable

In our schematic, we have shown a linear power amplifier used to drive the TEC. This is one approach to the output stage. The linear driver features very low noise, and can be made very efficient when it swings close to the supply rails. Driving a 2? TEC to its maximum current of 1.2 A, efficiencies of close to 90% are possible with some linear driver circuits. (See “Optoelectronics Circuit Collection”, <http://www-s.ti.com/sc/psheets/sbea001/sbea001.pdf>). The key to achieving good efficiency with a linear driver is to match the TEC driver amplifier characteristics with appropriate power supplies for your TEC.

A more “digital” approach is to use a switching or pulse-width modulated (PWM) type of driver. These circuits can achieve very high efficiencies, dissipating less heat in the driver. This can be attractive in these optical networking systems as space is usually at a premium, so large heatsinks are not desirable. The downside to this approach is that the switching noise may couple into the element being driven. For a TEC, this is usually not a problem, as long as adequate filtering is supplied to keep the ripple current within the specifications of the TEC.

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This PWM driver, built around a Texas Instruments DRV591, can supply up to ± 3 A to a TEC. The DRV591 has a fixed gain of 2.34, resulting in a transfer function of

$$V_o = V_{O+} - V_{O-} = 2.34(V_{IN+} - V_{IN-})$$

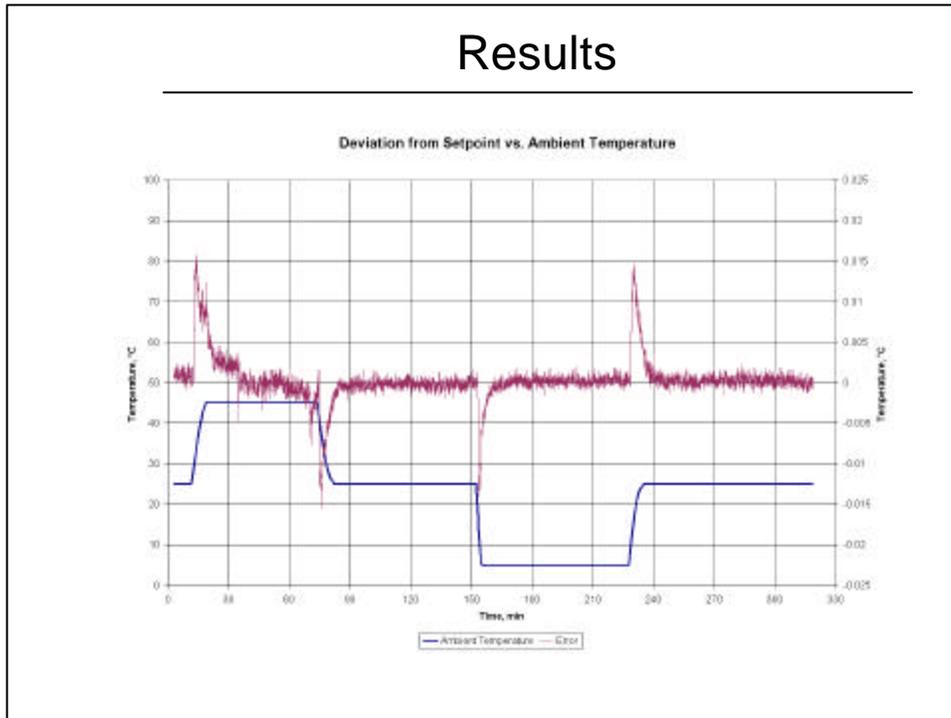
In our application, the TEC cannot have more than 2.72 V across it. This means that we must limit the voltage on V_{IN+} to less than 3.66 V, and the voltage on V_{IN-} to be more than 1.34 V. The OPA2342 circuit shown on the left side of this slide serves that purpose.

The DRV591 provides for fault monitoring; in this circuit we simply light up LEDs should an over current or over temperature condition occur, but these could just as easily be brought back to the microprocessor for reporting to the central computer.

A detailed drawing and discussion of this circuit can be found in the application note this is taken from, literature number SBAA072.

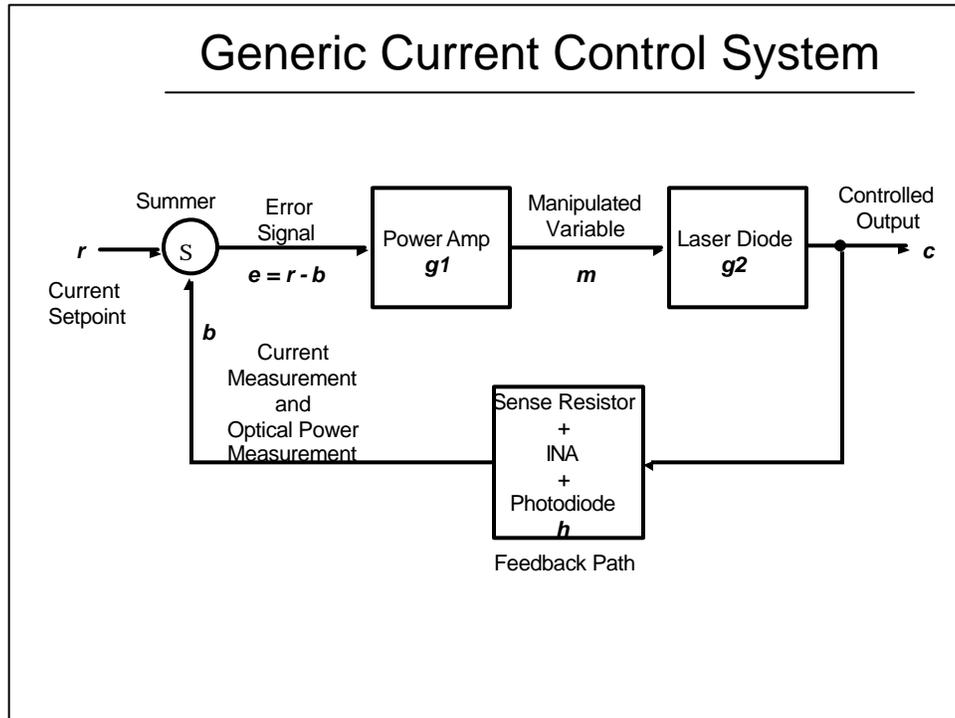
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Results



So, after all this, how did we do? The results are shown here. Temperature stability, even under a 20°C change in ambient temperature, was better than $\pm 0.005^\circ\text{C}$ at steady state. The cause of the higher error at higher ambient temperature may be the result of the fact that TECs generally are less efficient when cooling than heating.

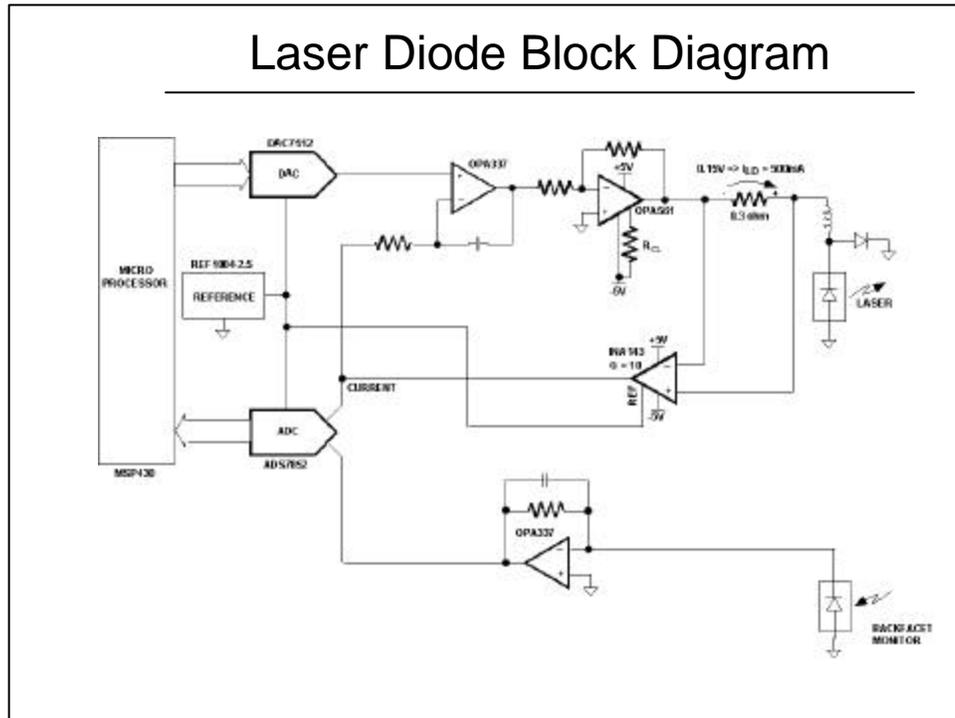
Note that for the most part, the temperature stability is within $\pm 0.002^\circ\text{C}$ over a long period, and is within $\pm 0.001^\circ\text{C}$ for short periods.



Now let's look at the current control problem: control the current through a laser diode, maintaining optimum optical power. The challenge in this control circuit is that the optical power monitor is not very accurate, and noise must be kept to a minimum.

As before, the setpoint for the current will come from a DAC. Two variables can be fed back to the system: the actual current measured, and the optical power output measured. The error signal then drives a power amplifier which drives the laser diode.

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This is the circuit that realizes our block diagram. The current through the laser is sensed with a sense resistor; the voltage across this resistor is amplified using a gain-of-10 instrumentation amplifier. This signal is fed back to an integrator, which integrates the difference between the DAC setpoint and the actual current. This signal drives the power amplifier.

This approach works well, but care must be taken with optimizing the loop for the appropriate transient response. As signals are added or dropped on the optical fiber, the optical power must change rapidly to maintain a constant power through the fiber. The proportional-integral method shown here may not be fast enough for some systems. In that case, the integrator/power amplifier combination can be replaced with a Howland Current Pump circuit (see "Optoelectronics Circuit Collection",

<http://www-s.ti.com/sc/psheets/sbea001/sbea001.pdf>).

The optical power is monitored by an op amp configured as a transimpedance amplifier. This signal is monitored by the ADC only in this schematic.

Reference

- ◆ Ratiometric mode can't be used
- ◆ Absolute reference
- ◆ Tolerance
 - Initial tolerance not a problem
 - Drift

In this control loop, our reference is important. Our sensor for feedback is the current sense resistor, and it is not able to be ratioed to the reference. The reference's inaccuracies and drift will therefore be part of the setpoint.

Fortunately, the laser is concerned mainly with changes in power once the initial power level is approximately correct. The problem is thus one of hoping that the back facet monitor diode's measurement of optical power is approximately correct. This is probably true as long as the output power is close to the rated power (remember the tracking ratio is better at higher powers!) and the monitor diode is kept at a constant temperature—and we took care of that in the previous few slides.

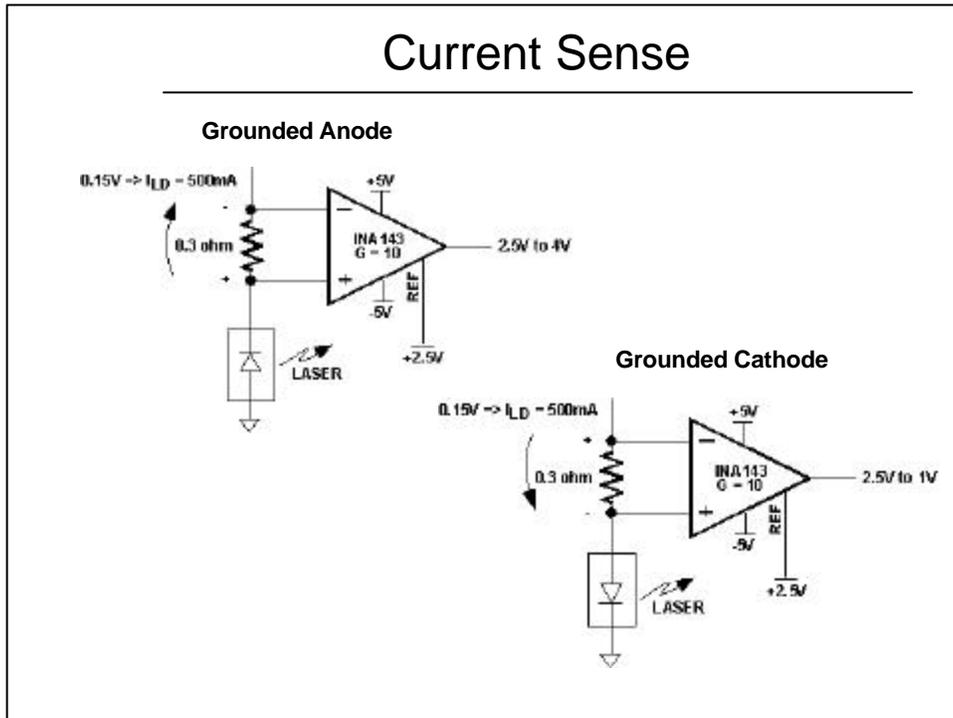
DAC Function

- ◆ Laser response » 0.5 mW/mA
- ◆ 12-bit DAC potentially gives us 60 μ W control
- ◆ Need good DNL

The laser in our system has a response of 0.5 mW per mA of current flowing through it. The setpoint for the DAC will come from the microprocessor, which will send the DAC a code representing a particular laser current, which in turn is proportional to an optical output power.

In our example, we've stuck with the 12-bit DAC we used previously, mainly for convenience. Note that using 12-bits potentially gives us 60- μ W resolution of optical power. This is likely not achievable due to the nonlinear power output of the laser diode.

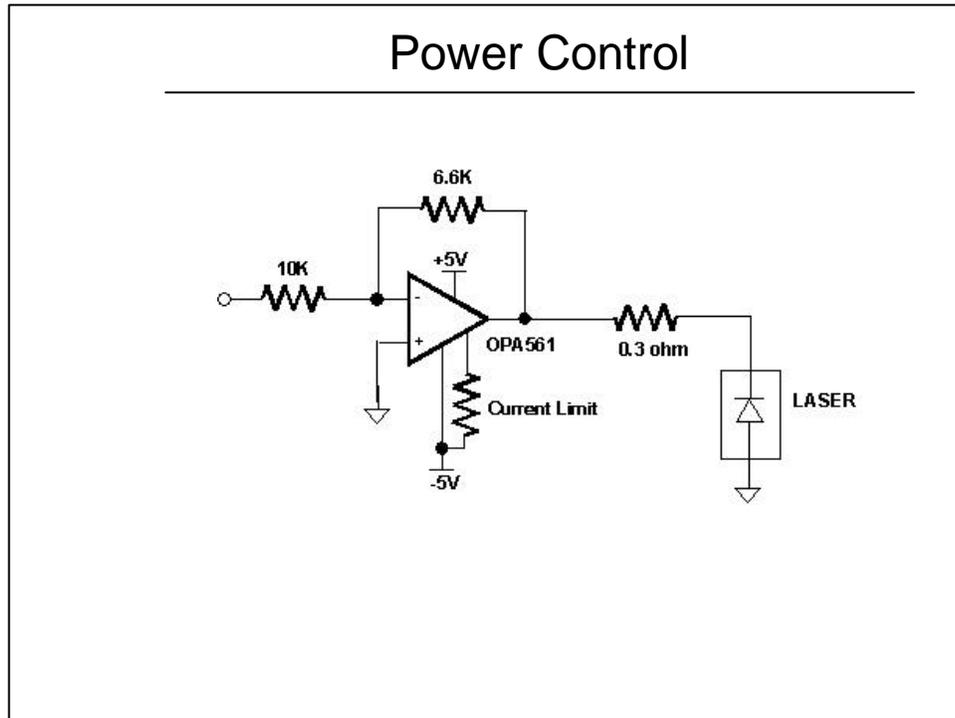
Current Sense



The laser current will be sensed by this circuit. For a given laser module, current can only flow one direction, but since we wanted to design a universal circuit, we made our driver and current sense amplifier bipolar.

Thus, with a grounded anode laser, current will flow as shown in the circuit on the left. The output voltage from the instrumentation amplifier will range from 2.5 V at zero current up to 4 V at 500 mA of current. Likewise, when current flows in the opposite direction, as with a grounded cathode laser, the output will range from 2.5 V at zero current down to 1 V at 500 mA.

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The power amplifier in this control loop is a linear power op amp. In the case of the laser drive, the noise in the drive current is critical, as noise here may couple into the signal path. Therefore, switching amplifiers are not widely used for laser drive applications.

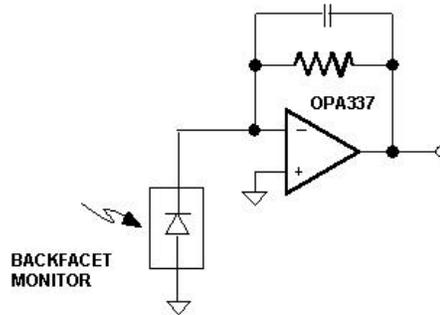
Many other linear drive circuits are possible. See “Optoelectronics Circuit Collection”,

<http://www-s.ti.com/sc/psheets/sbea001/sbea001.pdf>

Since the laser can be damaged by driving too much current through it, a current limit is a good idea. The OPA561 allows for a fixed current limit by tying the current limit pin to the negative rail through a resistor. A DAC could also be used to provide an adjustable current limit, if it can provide between 0 and 1.2-V swing above the negative rail (in this case, a swing from -5 V to -3.8 V).

Back Facet Diode Monitor

- ◆ Transimpedance amp
- ◆ Compensation



The optical power output of the laser diode is monitored by the back facet diode. The back facet diode is used in photovoltaic mode, meaning that no bias is applied to the diode. This means that all the current from the diode needs to be converted into a usable voltage.

This is done by using a transimpedance amplifier, as shown here. The feedback capacitor is chosen to minimize gain peaking.

For more information on photodiode circuits, see:

“Noise Analysis of FET Transimpedance Amplifiers”,
<http://www-s.ti.com/sc/psheets/sboa060/sboa060.pdf>

“Photodiode Monitoring With Op Amps”,
<http://www-s.ti.com/sc/psheets/sboa035/sboa035.pdf>

“Compensate Transimpedance Amplifiers Intuitively”,
<http://www-s.ti.com/sc/psheets/sboa055/sboa055.pdf>

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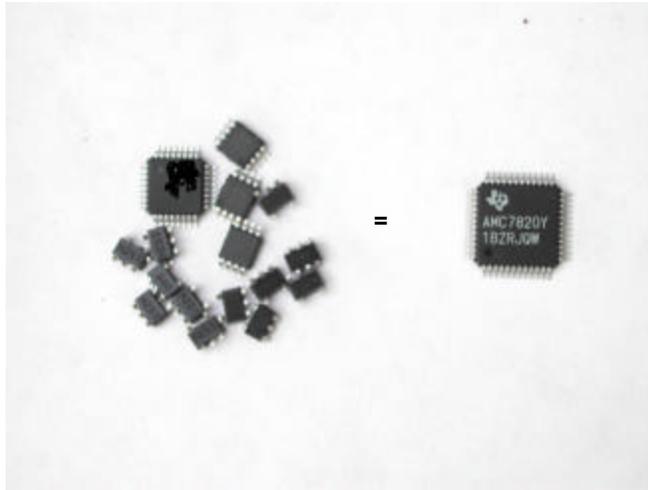
Monitor Function

Device	Resolution (Bits)	Sample Rate (kSPS)	Analog Inputs	DNL (\pm LSB)	INL (\pm LSB)	NMC (Bits)	SINAD (dB)	Package
ADS7824	12	40	4	0.5	0.5	12	72	DIP, SOIC
TLC2543	12	66	11	1	1	12	NA	DIP, SOIC, PLCC, SSOP
ADS7844	12	200	8	1	1	12	72	SSOP
TLV2544	12	200	4	1	1	12	69	SOIC, TSSOP
ADS7852	12	500	8	1	1	12	71	TQFP
ADS7864	12	500	6	1	1	12	70	TQFP

The output from the back facet monitor goes to the ADC for conversion into digital and subsequent reporting to the central processor. Again we choose a 12-bit ADC simply because it's available and similar to the one for the TEC. In fact, for most systems, there will be only one ADC for both TEC and laser diode control functions, and it will be a multichannel ADC.

Here now we must consider the latency introduced by the ADC if we were to use the optical power as a feedback mechanism. In the system we've just designed, the optical power would have to be converted by the ADC, understood by the host processor, and adjustments made to the DAC setpoint as needed. As channels are added or dropped from the fiber, changes in optical power must be responded to very quickly—in less than a microsecond. If the ADC were to be used in this manner, a much faster ADC would be required. Likewise, a faster DAC would be required, processor overhead would have to be quite small, and the power drive circuit would have to be the Howland Current Pump rather than the proportional-integral power amplifier we've used.

Integrated Approach

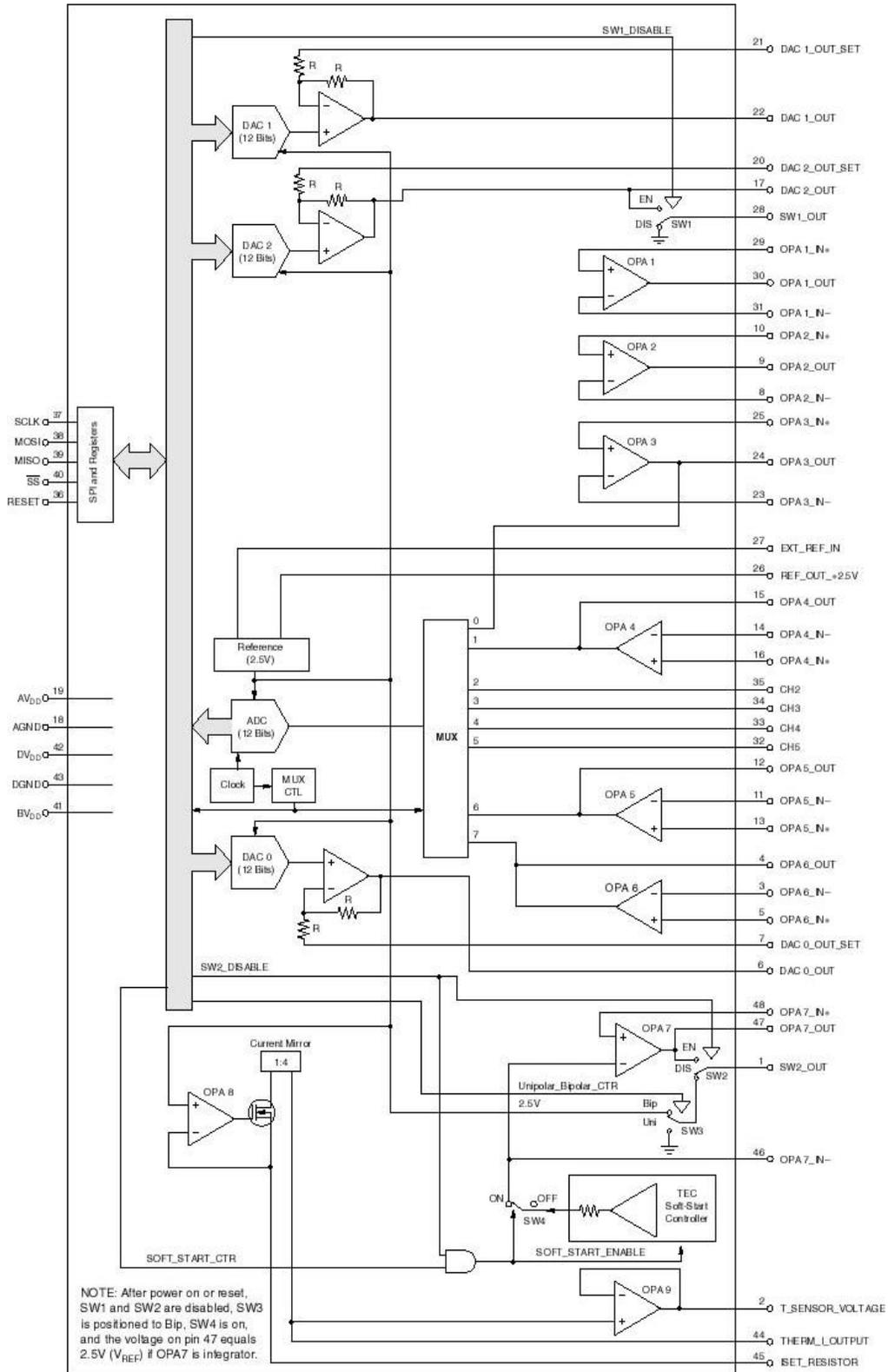


After having looked at these two loops, you can see that they are similar, but require several components each. References, DACs, ADCs, op amps, current sources for the thermistor—not to mention the power drive circuitry.

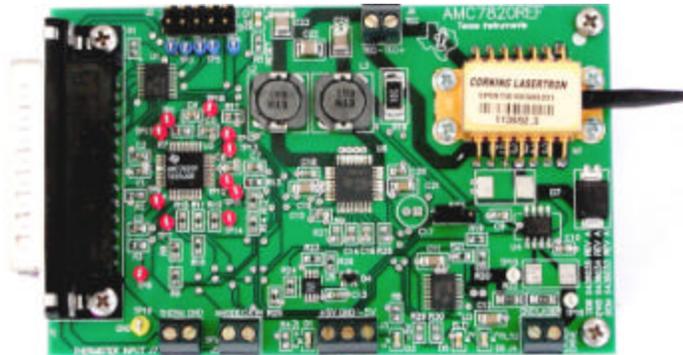
Since space is at a premium in DWDM systems, how can you fit all this into the space required? One solution is to have an integrated circuit that combines the most common of these functions together to make realizing these systems easy.

That device is the AMC7820 from Texas Instruments.

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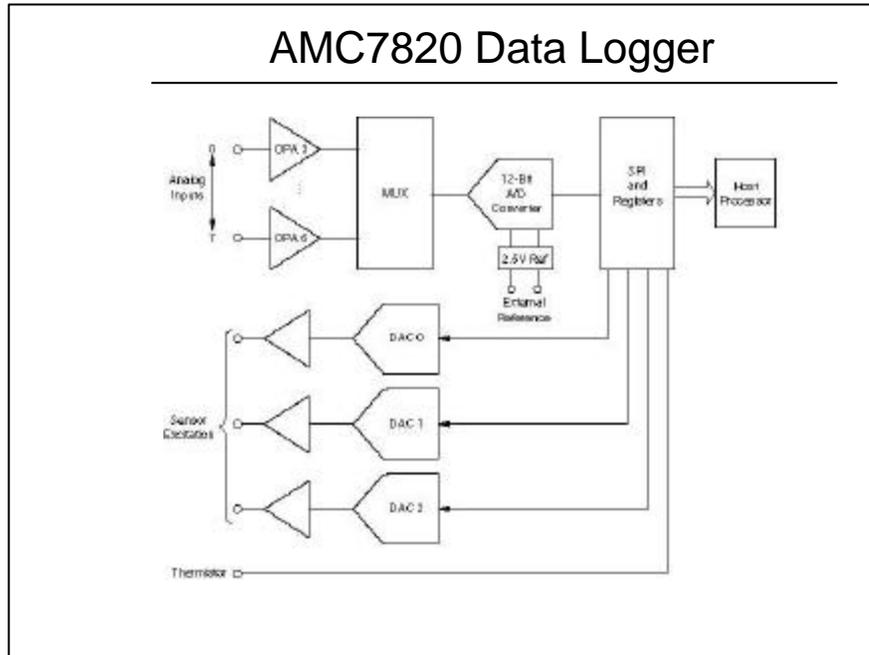
AMC7820 Application



This is a photo of the board built from the design presented. This credit-card sized circuit realizes the complete laser and TEC control loops of an EDFA amplifier. The pump laser module can be seen in the upper right-hand corner of the board.

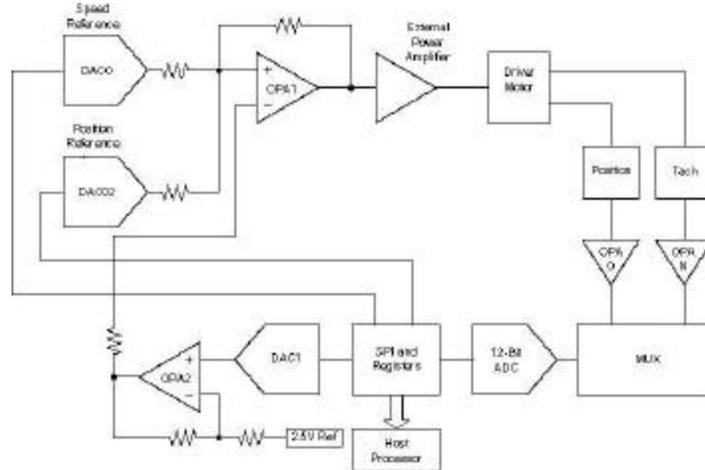
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Additional Control Applications



The AMC7820 makes an excellent data logger because it can multiplex up to eight channels of data, condition four sensors, record the data, and transmit the data to a host processor. The data on six of the multiplexed channels can be level shifted and amplified by the internal op amps and reference. The three internal DACs can be conditioned with internal op amps as sensor excitation, and the thermistor channel is available for thermistor excitation and linearization. A host computer controls the data logger through a SPI serial interface. The ADC runs at 100 kHz, so the data rate exceeds several kHz.

Speed/Position Control System



This is a dual mode control system where the speed ramp up/down is controlled independent of the position control. The host processor receives and sends data to the AMC7820 through the SPI serial interface. The speed profile is set by DAC0, and the profile can be modified on the fly because it is under software control. Likewise, the host processor controls the position. Because the host processor gets speed and position data from the SPI interface, it can determine when to modify the speed profile or position setting. Both speed and position data are obtained from external sensors, and the data is amplified/level shifted to be compatible with the 12-bit ADC.

Advantages of Higher Integration

- ◆ Reliability
- ◆ Space
- ◆ Cost

Control solutions using data converters offer many distinct advantages over traditional analog solutions. Control solutions using devices which integrate multiple converters such as the AMC7820, which includes a 12-bit ADC and three 12-bit DACs, offer the added advantages of higher reliability, reduced space and reduced system cost.

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Mailing Address:

Texas Instruments
Post Office Box 655303
Dallas, Texas 75265