Application Report
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An Optical Amplifier Pump Laser Reference Design Based on the AMC7820

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ABSTRACT

The AMC7820 is an integrated circuit designed for analog monitoring and control. Its features are put to use in this reference design for laser and thermoelectric cooler control in EDFA and Raman optical amplifiers. The resulting circuit fits into a credit-card sized space.

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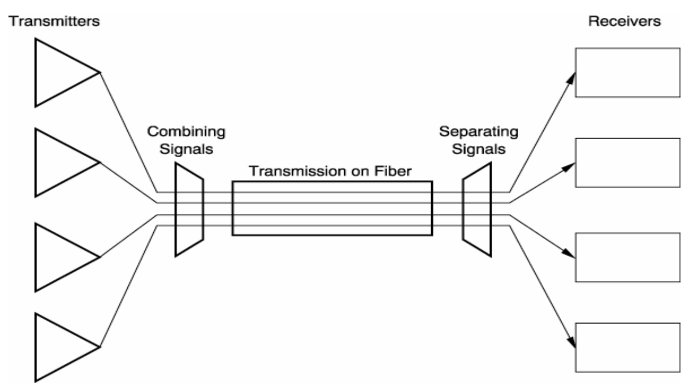
Introduction

Optical networking is becoming a more important networking option, and it presents some interesting control system challenges. One of these challenges is controlling the laser diode in a DWDM system.

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 wavelengths. This concept is illustrated in Figure 1.

Figure 1. DWDM Multiplexes Many Signals Onto One Fiber.



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.

Erbium is a rare-earth element that, when excited, emits light around 1.54 micrometers—the low-loss wavelength for optical fibers used in DWDM. A weak signal enters the erbium-doped fiber, into which light at 980nm or 1480nm is injected using a pump laser. This injected light stimulates the erbium atoms to release their stored energy as additional 1550nm light. As this process continues down the fiber, the signal grows stronger. The spontaneous emissions in the EDFA also add noise to the signal; this determines the noise figure of an EDFA.

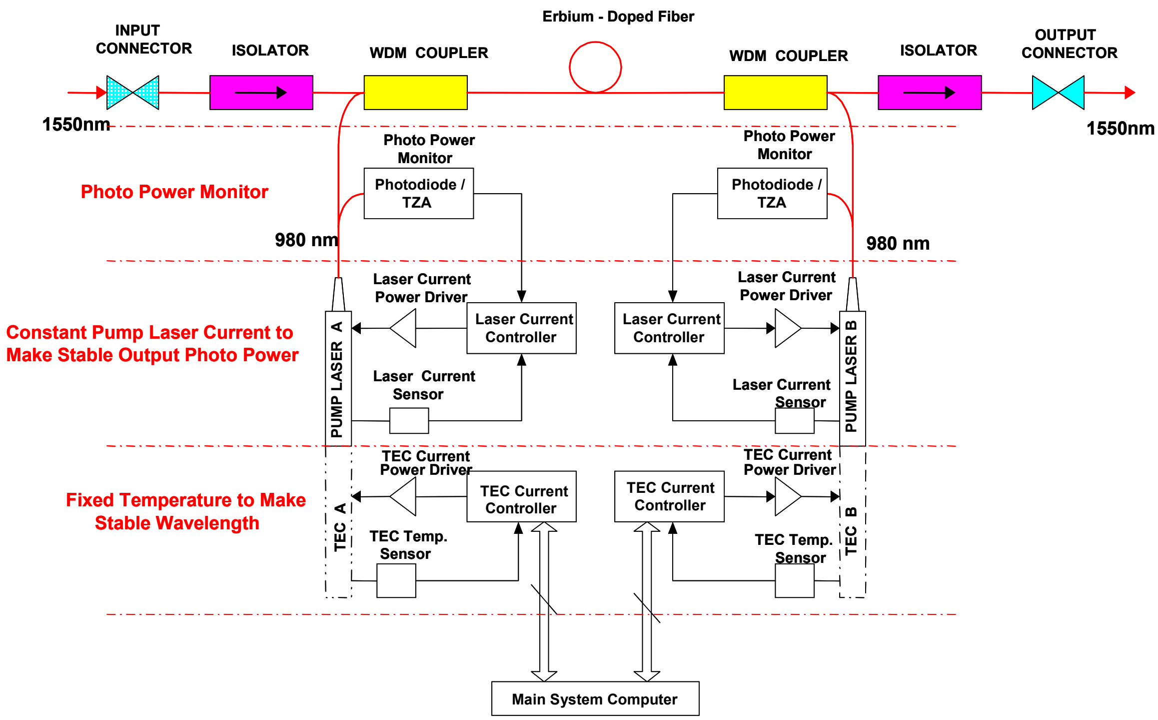
The key performance parameters of optical amplifiers are gain, gain flatness, noise level, and output power. EDFAs are typically capable of gains of 30dB or more and output power of +17dB or more. The signal gain provided with an EDFA is inherently wavelength-dependent, but it can be corrected with gain flattening filters, which are often built into modern EDFAs.

Low noise is a requirement because noise, along with signal, is amplified. Because this effect is cumulative, and cannot be filtered out, the signal-to-noise ratio is an ultimate limiting factor in the number of amplifiers that can be concatenated and, therefore, the length of a single fiber link. In practice, signals can travel for up to 120km (74mi) between amplifiers.

Erbium-Doped Fiber Amplifier Basics

Figure 2 shows a 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.

Figure 2. EDFA Power Monitoring and Control.



There are actually several control loops here. Inside the laser module, there are control loops for the pump laser current and the TEC, to control optical power and temperature. These loops are relatively slow, almost DC control problems.

The loop outside the laser module, however, is much faster and this is the loop that monitors the input and output optical power. This loop must be fast because the optical power must be quickly adjusted when adding or dropping channels, to control the transient response of the EDFA. Dropping channels can give rise to surviving channel errors, since the power of these channels may surpass the threshold for nonlinear effects such as Brillouin scattering. Adding channels can cause errors by depressing the power of surviving channels below the receiver threshold. Response times of this loop are required to be in the range of 0.85μs to 3.75μs.

Often, a fast Analog-to-Digital Converter (ADC) is used to get the initial fast response time, and a slower, higher-resolution converter is used to stabilize the loop to its final value. The design presented in this application note addresses the slower control loop problem, which is to control current through a laser diode to provide optimal optical power output, while maintaining tight control of the laser's temperature so that the laser diode will stay on the desired 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 significant current is driven 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 controlled by the amount of current through the TEC. This current, as well as the pump laser diode current, must be precisely monitored and controlled.

This means controlling the temperature within ±0.1°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.

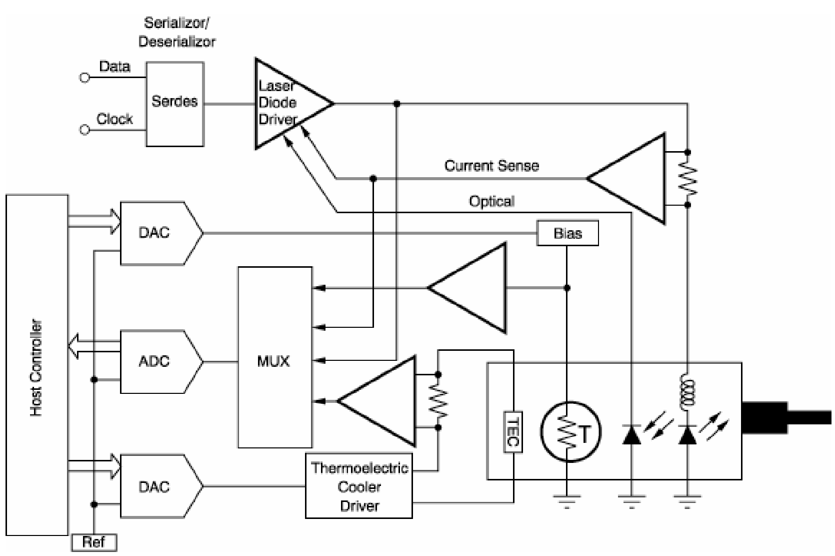
Since these optical networking components are part of a large system, a standard has been established for monitoring and reporting the status of each network component. This is called the Management Information Base, and for the EDFA, parameters such as optical SNR, pump laser temperature, pump laser current, and others must be able to be reported back to a central computer that monitors these parameters. This is done to insure quality of service (QoS) and to detect faults in the system. For this reason, these parameters are converted to digital through an ADC.

Pump Laser Module

The pump laser diode module can be seen in Figure 3. 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 that controls the thermoelectric cooler. Various critical parameters of the system are monitored and controlled by the ADC and the digital-to-analog converter (DAC).

Figure 3. DWDM Transmission System.



Laser Diode

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

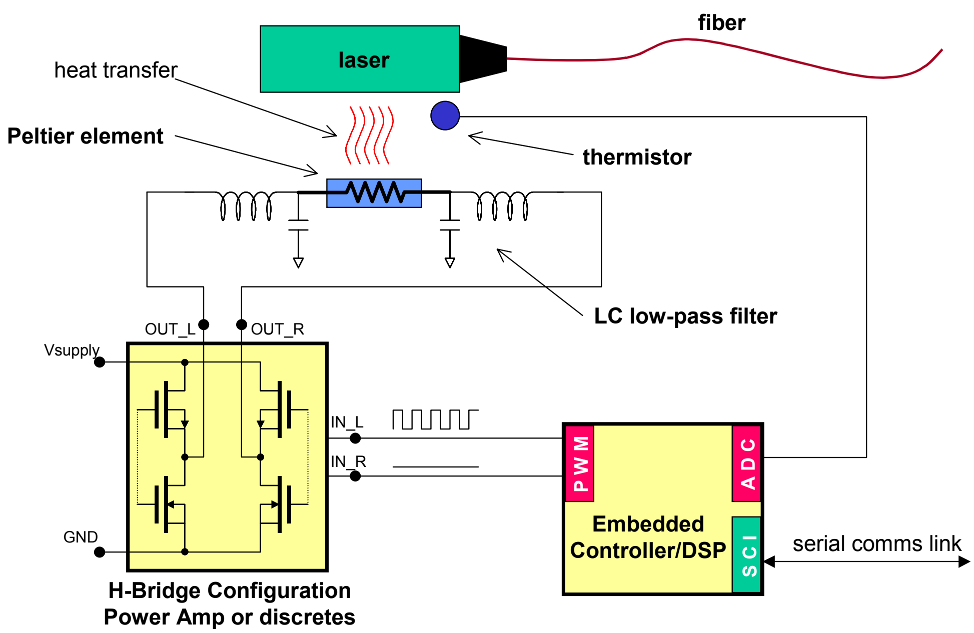
The laser module for this design is a 975nm pump laser, with 250mW output power. Laser modules require drive currents in the range from 300mA up to 3A. The particular laser used in this design requires a minimum threshold current of 35mA to operate, and can be driven up to 500mA when achieving maximum power output.

Thermoelectric Cooler (TEC)

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

The thermoelectric cooler consists of a Peltier element in close contact with the laser diode, as shown in Figure 4. 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.

Figure 4. Thermoelectric Cooler Block Diagram.



For system stability, note that maintaining ±0.1°C temperature stability with the newer laser still may result in a change of 0.002nm out of the 975nm center wavelength. This is a change of ±2ppm. 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, as overall stability of approximately ±4ppm is needed in these systems.

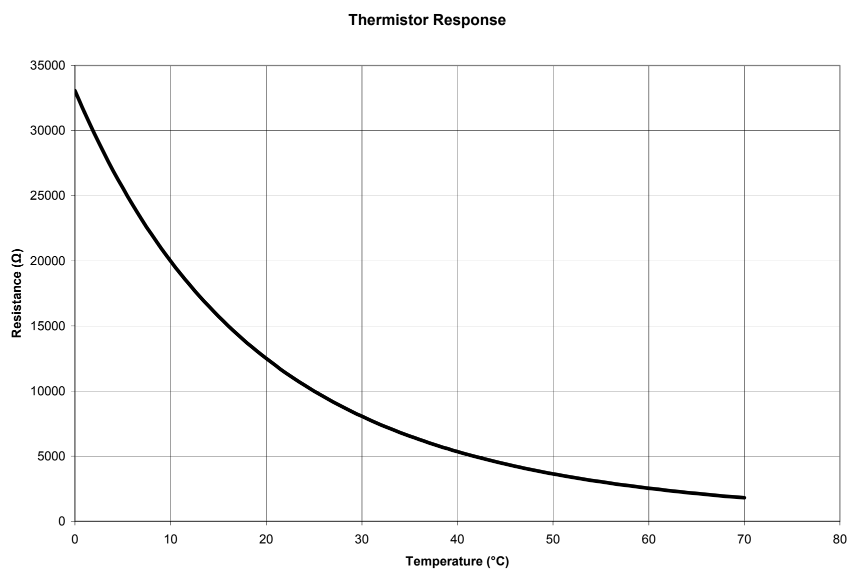
The thermoelectric cooler in the laser module used can draw up to 1.8A when the difference between one side of the cooler and the other side is 50°C. The TEC must not have more than 3.4V applied across it, as higher voltages will damage the element.

Note that there are no accuracy specifications for the TEC — this is a device that 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.

Thermistor

The thermistor used in the laser module has a negative temperature coefficient. The nominal value of the thermistor is 10K ±500Ω, at 25°C. Like all thermistors, its response is nonlinear over a wide range of temperature.

Figure 5. Thermistor Response Curve.



Since the thermistor is the transducer for measuring temperature, and the system must measure and control temperature within 0.01°C, this transducer must be linearized. Fortunately, the characteristic of this thermistor is known, so the nonlinearity can be taken into account.

Back Facet Monitor

The diode formed on the back facet of the laser diode can be used as a photodiode to monitor the optical power output. Typically, this diode is used only as a coarse indicator of laser power, as the back facet diode is not very accurate. In the laser module used in this design, the responsivity of this diode is typicially 7µA/mW, but can be as low as 2µA/mW and as high as 30µA/mW.

Tracking ratio is a specification worthy of attention. It is the linearity of measured power versus the current output from the diode. At first glance, for the laser module used in this design, 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 the system must be designed to handle a dynamic range that will accommodate the lowest as well as highest responsivity.

AMC7820: An Ideal Device for Control Loop Solutions

The EDFA pump laser design requires two control loops: a temperature control loop, and a current control loop for the laser diode. Setpoints for each loop will be under computer control, requiring DACs, and monitoring of critical parameters must be done, requiring ADCs. Most of the actual control loop functions can be realized in the analog domain, so several op amps are also needed. While this function could be accomplished by putting discrete devices down on a printed circuit board, this would require significant space. EDFAs are generally put in places where space it at a premium.

The AMC7820 is a device that contains all the functions needed for this design. The AMC7820 is a complete analog monitoring and control circuit in a 48-pin TQFP package that includes an 8-channel, 12-bit ADC, three 12-bit DACs, nine operational amplifiers, a thermistor current source, an internal +2.5V reference, and an SPI™ serial interface. It is ideal for multi-channel applications where low power and small size are critical.

In the following sections, the features of the AMC7820 will be put to use in developing solutions to the control problems presented.

Thermoelectric Cooler Control

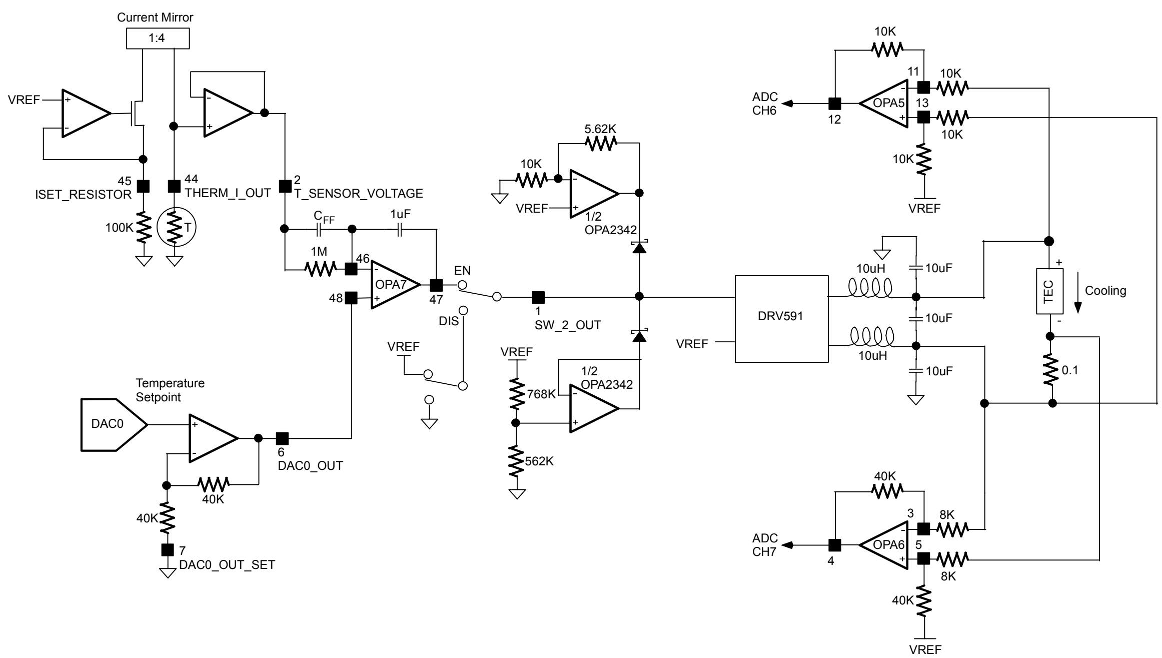
The first problem is to control the temperature of the laser diode. In this pump laser example, the wavelength needs to be controlled to within ±0.5nm of the initial wavelength. This means that only drift is a problem, not the initial value. As long as the temperature is close to the 25°C that the laser wants to operate at, the pump will still work, but its stability is most critical.

Since many lasers have a 1nm/°C tempco, this means that the temperature should be controlled to within ±0.5°C maximum. However, since drift appears as noise in the amplifier, any change will degrade the optical signal-to-noise ratio. So the design goal is to achieve ±0.1°C drift to minimize noise. This will also give ample room for drift due to amplifier aging. (Note that the actual laser used is much more forgiving of temperature change, with a much lower tempco than 1nm/°C. While this is nice, the system is designed to control within ±0.1°C, to achieve maximum SNR.)

The temperature control loop is shown in Figure 6. Black squares denote pins on the AMC7820. The temperature setpoint is determined by the output of DAC0, which has a 0V to 5V range. The thermistor is biased with a 100μA current, which is supplied by the AMC7820's internal current source. At 25°C, this will result in 1V dropped across the thermistor. This voltage is applied to the integrator built around OPA7. As the difference between the thermistor voltage and the setpoint increases, the integrator will ramp up or down.

A key feature of the AMC7820 is the inclusion of switches to disable the TEC drive. This switch comes off the output of the integrator. When connected to the integrator, the error voltage is passed along to a limiter circuit, and then to a DRV591 PWM power driver. This circuit will drive current through the TEC in either direction, to either heat or cool. OPA5 and OPA6 are configured as difference amplifiers to sense the TEC voltage and current, respectively.

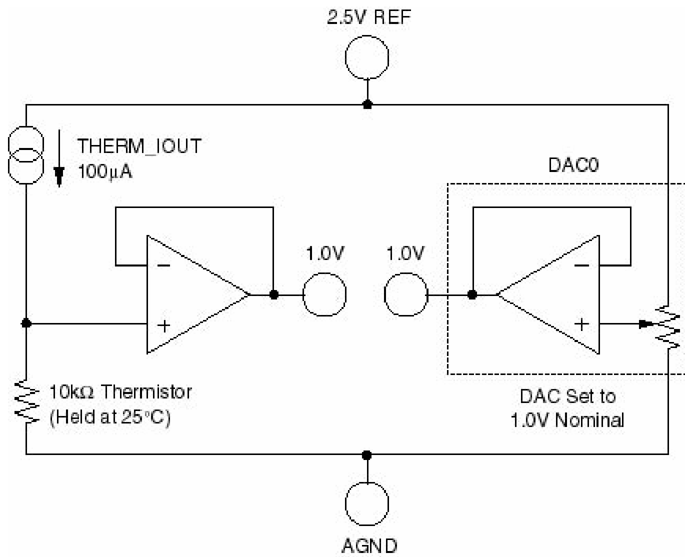
Figure 6. TEC Control Loop.



DAC0 determines the temperature setpoint, and affords temperature resolution of approximately 0.03°C per LSB. The DAC requires a reference voltage; the internal AMC7820 reference will have an initial tolerance of 2%, and a drift of 10ppm/°C. How can this error be eliminated?

The answer is simple: use the same reference for both the DAC and the thermistor, as shown in Figure 7. 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 the control loop must do 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.

Figure 7. Temperature Measurement with Ratiometric Reference.



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

Thermistor

As noted earlier, the thermistor characteristic is not linear, and this nonlinearity must be taken into account. By knowing the characteristic of the thermistor, and the excitation it is being provided, the microprocessor driving the setpoint DAC can calculate the voltage that corresponds to a certain temperature.

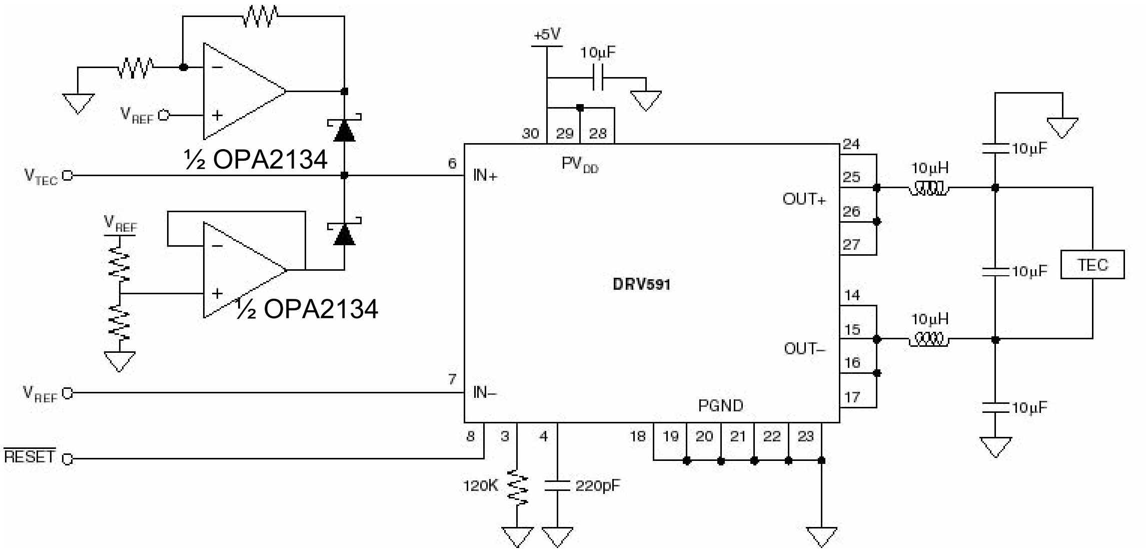
Actually, the calculation will find a code that is a ratio of the output to full-scale; this code is what is sent to the DAC. Remember, since the converter and the thermistor are all using the same reference, the absolute voltage doesn't matter; only the ratio to full-scale matters.

Driver

In this design, a switching PWM driver is used to drive the TEC. This is one approach to the output stage. A linear driver features very low noise, and can be made very efficient when it swings close to the supply rails. Driving a 2Ω TEC to its maximum current of 1.8A, 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.

Switching or Pulse-Width Modulated (PWM) types of drivers, as used here, 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.

Figure 8. Class D Power Driver for the TEC.



The PWM driver circuit shown in Figure 8, built around a Texas Instruments DRV591, can supply up to ±3A to a TEC. The DRV591 has a fixed gain of 2.34, resulting in a transfer function of:

$$V_O = V_{O+} - V_{O-} = 2.34\left(V_{IN+} - V_{IN-}\right)$$

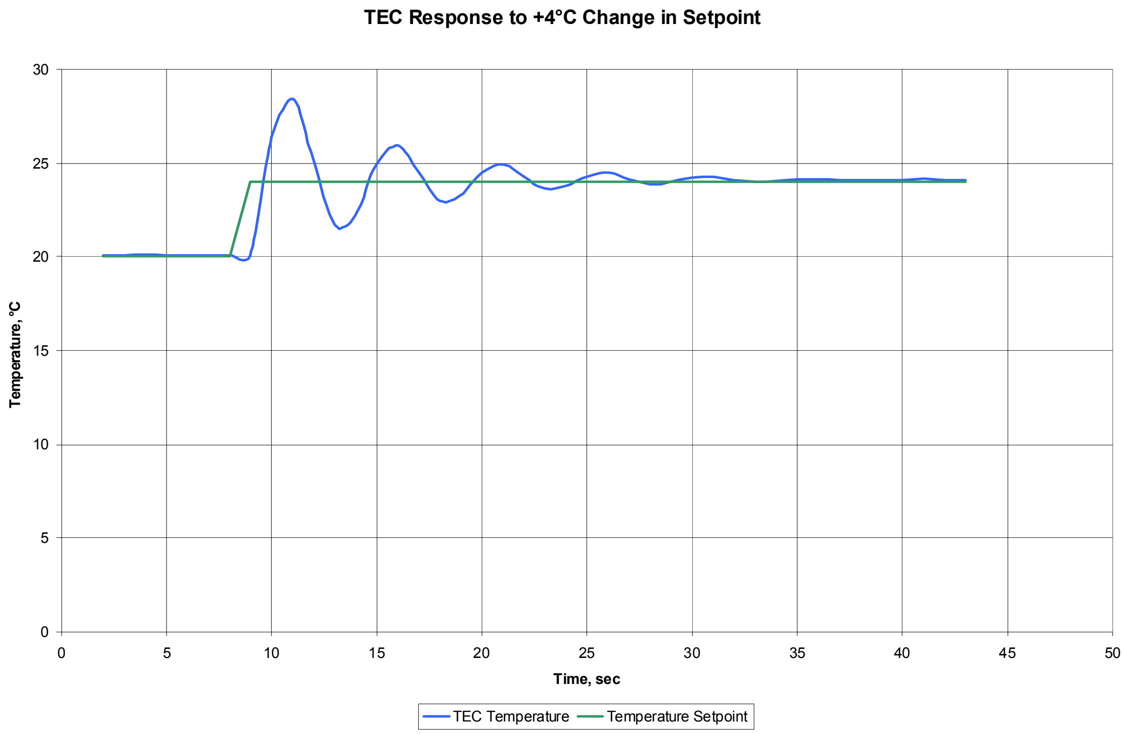
In this application, the TEC cannot have more than 2.72V across it. Since V_{IN-} is tied to the 2.5V reference, this means that the voltage on V_{IN+} must be limited to less than 3.66V and must be more than 1.34V. The OPA2342 circuit shown on the left side of Figure 8 serves that purpose.

The DRV591 provides for fault monitoring; in this circuit LEDs light up 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.

Stability

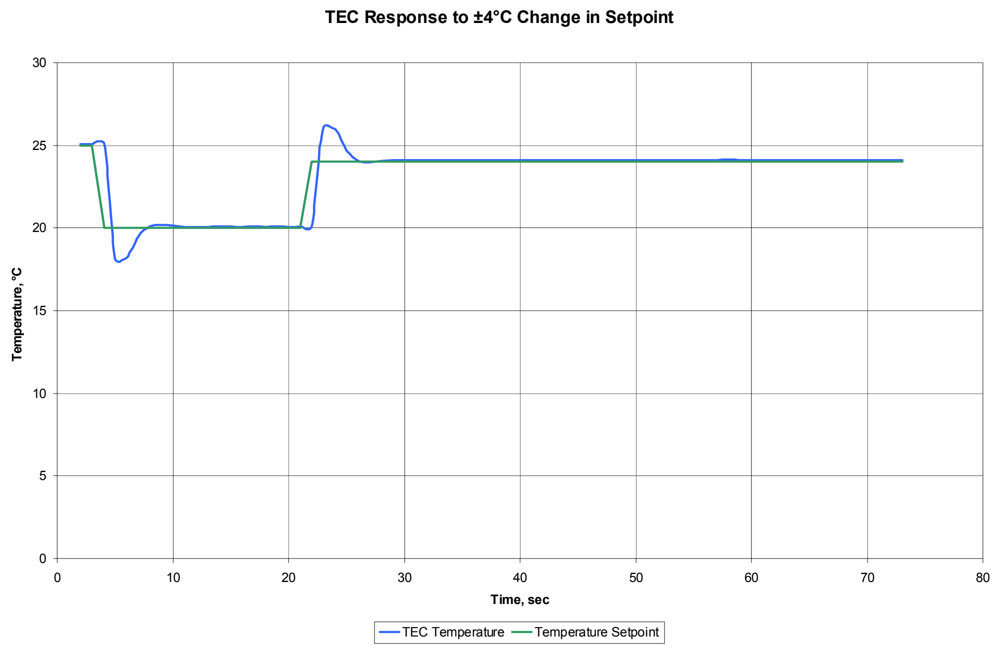
As the temperature setpoint is changed, the loop will attempt to force the temperature to the setpoint. If the error amplifier/integrator is not compensated properly, the loop will overshoot and ring for quite some time. As seen in Figure 9, a 4°C change in setpoint results in the loop taking over 30 seconds to stabilize.

Figure 9. TEC Response with no Compensation.



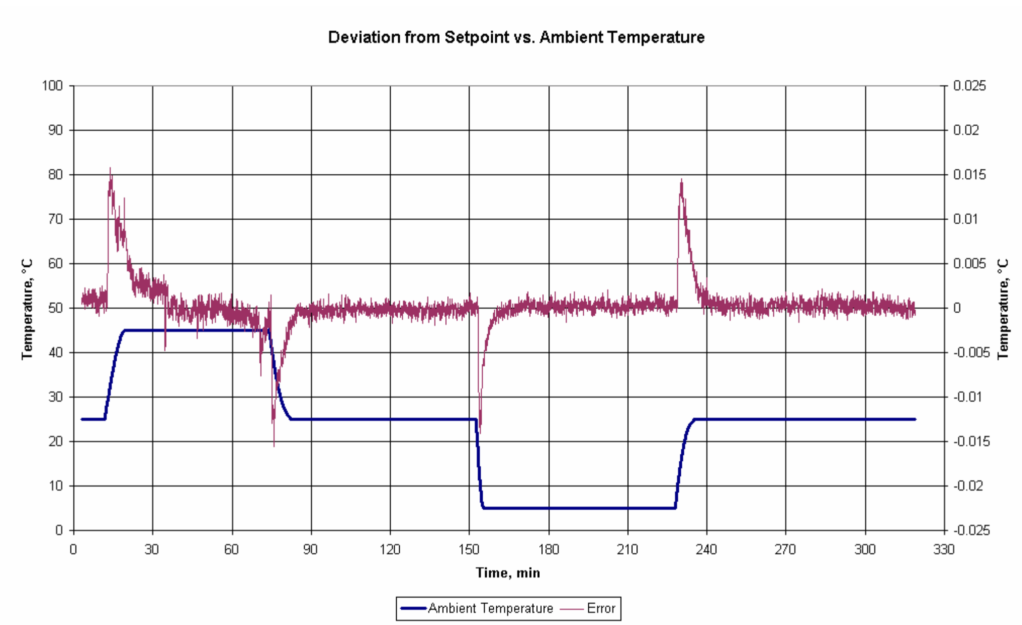
Adding a feedforward capacitor (C_{FF}) to the integrator greatly reduces the overshoot and the time needed for the loop to stabilize. See Figure 10 for a 1µF capacitor used as the feedforward capacitor; the system is still a bit underdamped. Note that the response time has reduced to about 5 seconds.

Figure 10. TEC Response with Compensation.



The resulting operation of the TEC control loop is shown in Figure 11. Temperature stability, even under a 20°C change in ambient temperature, was approximately ±0.005°C at steady state. Note that for the most part, the temperature stability is within ±0.002°C over a long period, and is within ±0.001°C for short periods.

Figure 11. Deviation from Setpoint vs Actual Temperature.

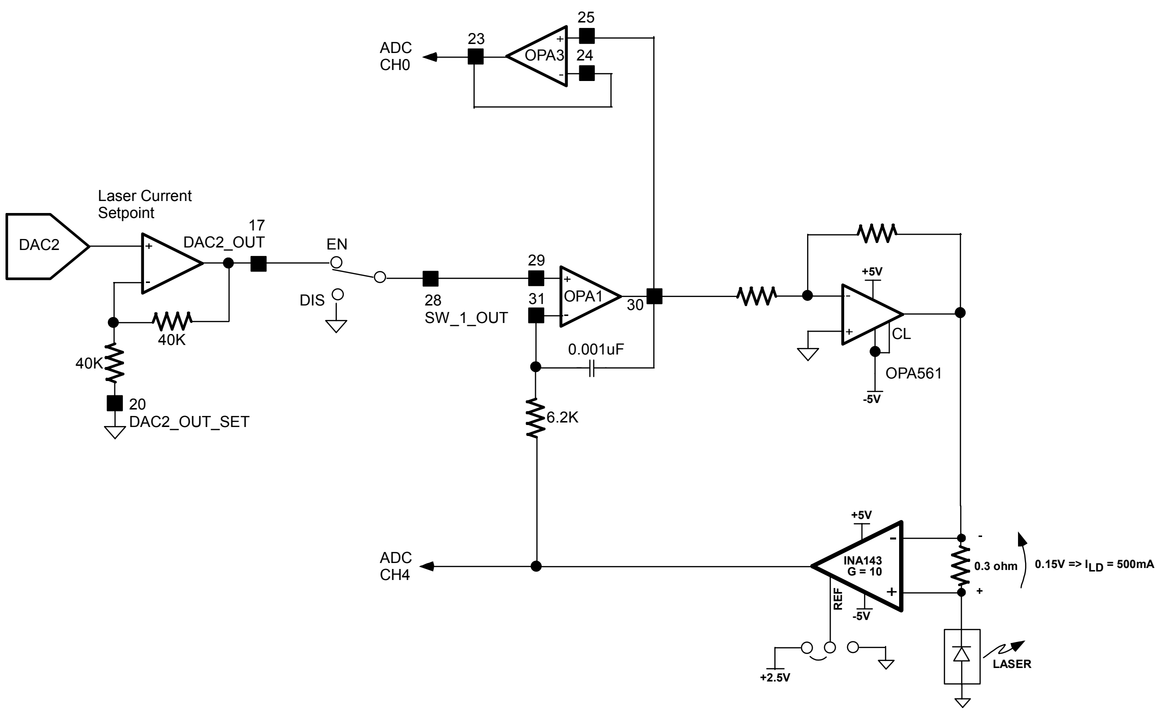


Laser Control

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 this design, the back facet diode is used as a rough estimate of the optical power because the initial accuracy of the back facet monitor is only ±20%, and at any given power level, only stable within ±1%. The actual control, however, is not dependent upon optical power but on a current level that the system will specify and measure. The sensitivity of the laser diode to current is approximately 0.5mW/mA in its linear region.

The laser control loop is shown in Figure 12. As before, the setpoint for the current will come from a DAC, in this case the AMC7820's DAC2. 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 built around OPA1, which integrates the difference between the DAC setpoint and the actual current. This signal drives the external linear power amplifier, which is an OPA561.

Figure 12. Laser Control Loop



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).

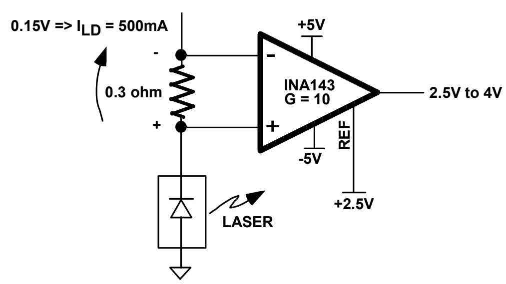
In this control loop the reference is important. The sensor for feedback is the current sense resistor and it is not able to be ratioed to the reference. The reference's inaccuracies and drift will therefore be part of the setpoint.

Fortunately, the laser is concerned mainly with changes in power once the initial power level is approximately correct. The laser in this system has a response of approximately 0.5mW 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.

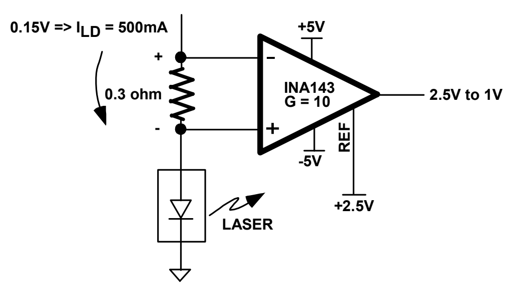
Current Sense

The circuit shown in Figure 13 will sense the laser current. For a given laser module, current can only flow one direction, but this design was to be a universal circuit, so the driver and current sense amplifier are designed to be bipolar.

Figure 13. Current Sense Circuits.



GROUNDED ANODE



GROUNDED CATHODE

Thus, with a grounded anode laser, current will flow as shown in Figure 13. The output voltage from the instrumentation amplifier will range from 2.5V at zero current up to 4V at 500mA of current. Likewise, when current flows in the opposite direction, as with a grounded cathode laser, the output will range from 2.5V at zero current down to 1V at 500mA.

If the laser polarity is known, this circuit could be modified to only allow unipolar operation, by grounding the INA143's reference pin instead of connecting it to 2.5V. The input polarity of the instrumentation amplifier would also need to be reviewed to make sure that the sense of the signal would be correct for feeding back to the control loop. Increasing the size of the sense resistor, to take advantage of an increased signal swing, would be possible. This would allow the ADC to realize increased current resolution for monitoring purposes.

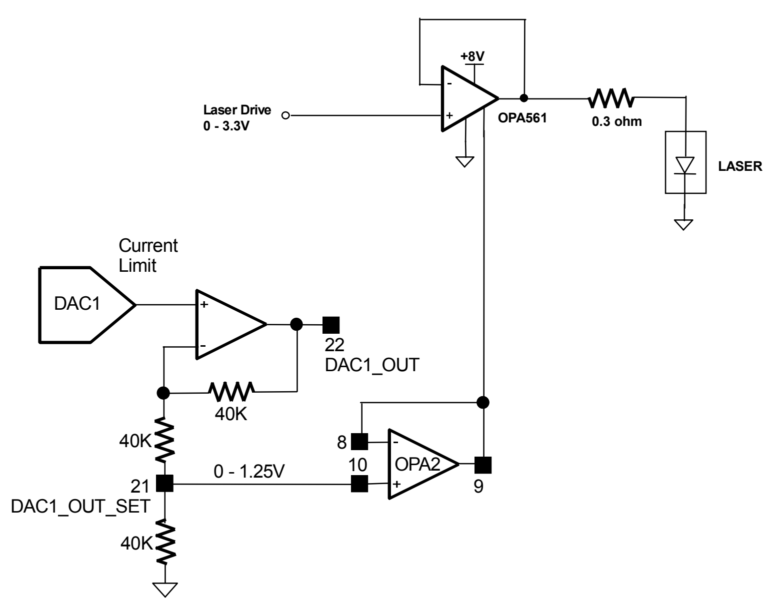
Laser Driver

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.

Driving too much current through it can damage the laser. A current limit on the laser driver is therefore 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 0V and 1.2V swing above the negative rail (in this case, a swing from –5V to –3.8V). For example, in a circuit with a grounded cathode, the OPA561 could operate off of a single supply (note that the OPA561 requires a minimum +7V supply in single supply mode). In that case, DAC1 could be used as shown in Figure 14 to control the current limit. Note using the internal resistors for the DAC as part of a voltage divider to cause the DAC output swing to be between 0V and 1.25V.

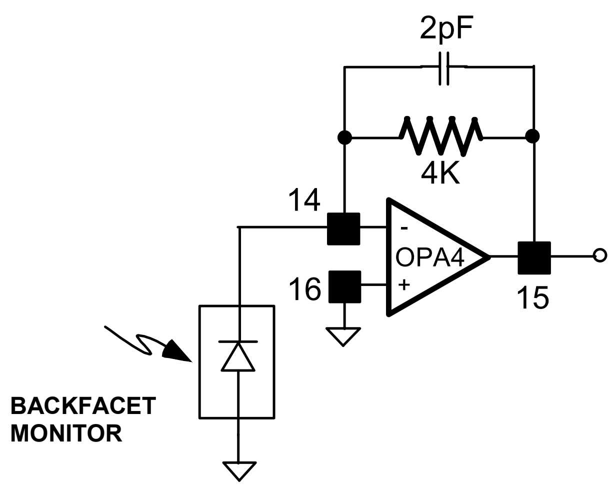
Figure 14. Digitally-Controlled Current Limit.



Optical Power Monitor

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. Using a transimpedance amplifier, as shown in Figure 11, does this. The feedback capacitor is chosen to minimize gain peaking.

Figure 15. Back Facet Diode Monitor.



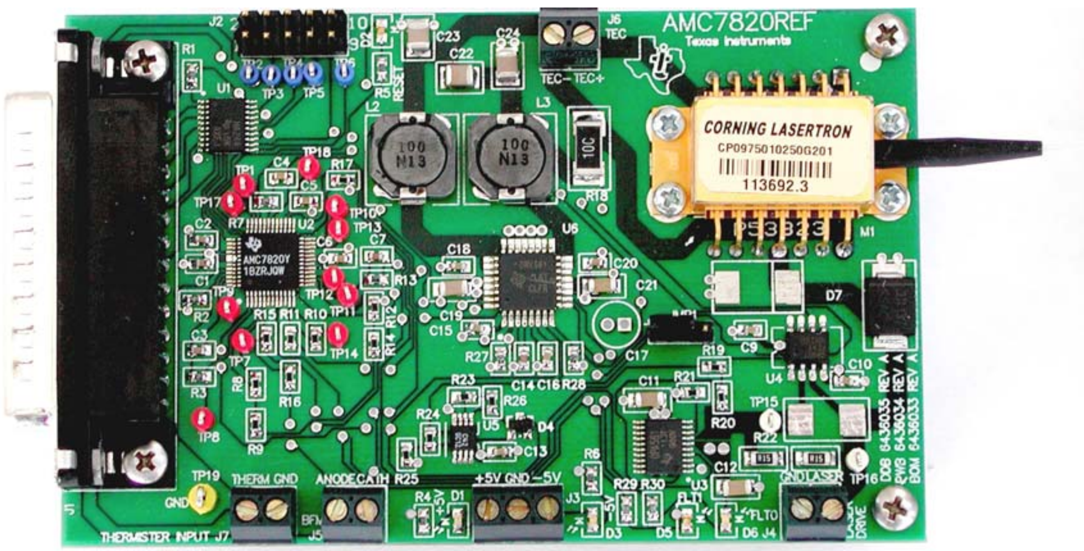
The ADC monitors the output signal from this circuit, in hopes that the back facet monitor diode's measurement of optical power is approximately correct. This is probably true as long as the output power is close to the rated power (remember the tracking ratio is better at higher powers!) and the monitor diode is kept at a constant temperature—and that has been taken care of already by the TEC.

Now we must consider the latency introduced by the ADC if the optical power is used as a feedback mechanism. In the system 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 used.

Conclusion

Figure 16 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.

Figure 16. Complete AMC7820-Based EDFA Pump Laser System.



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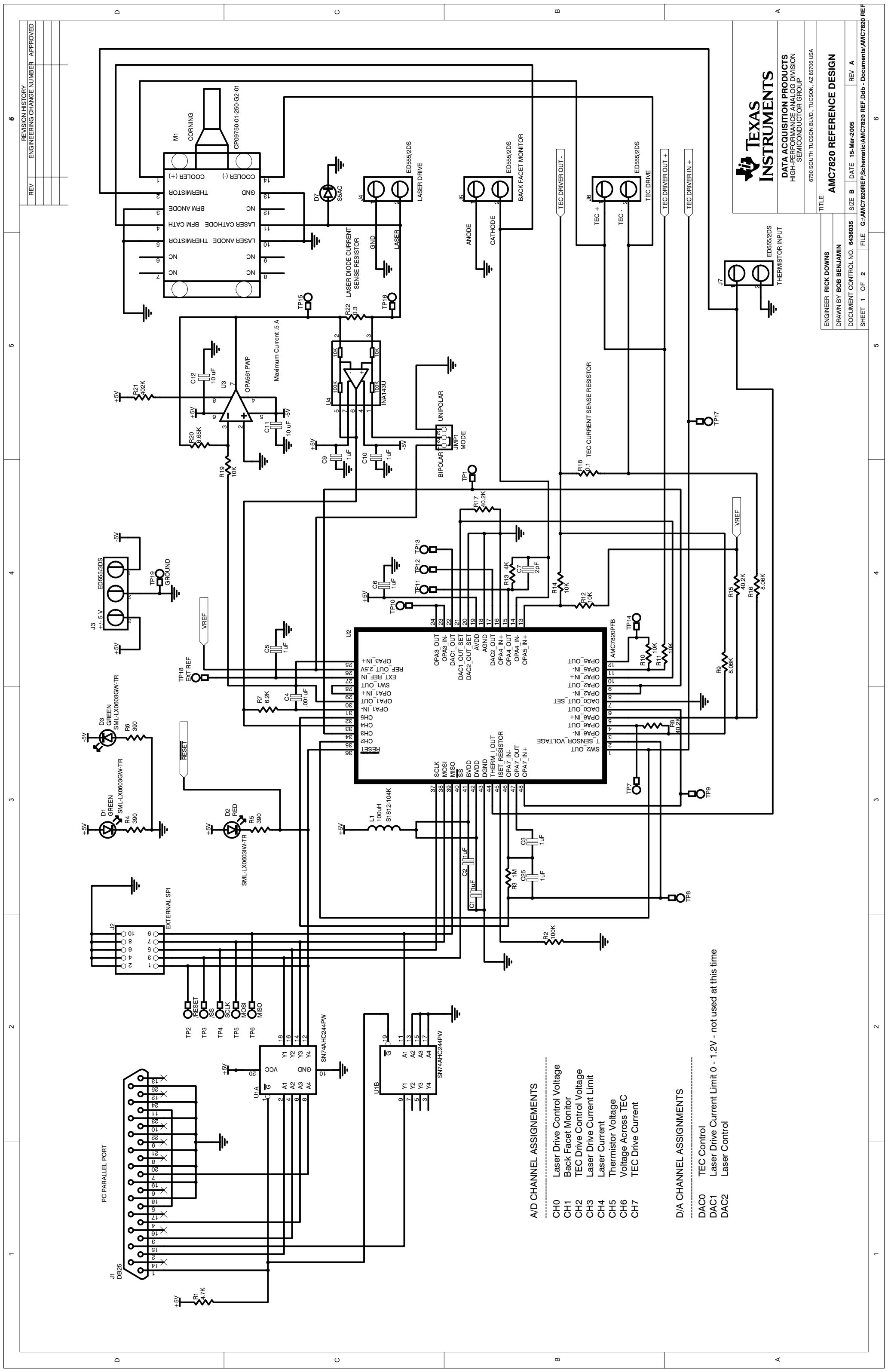
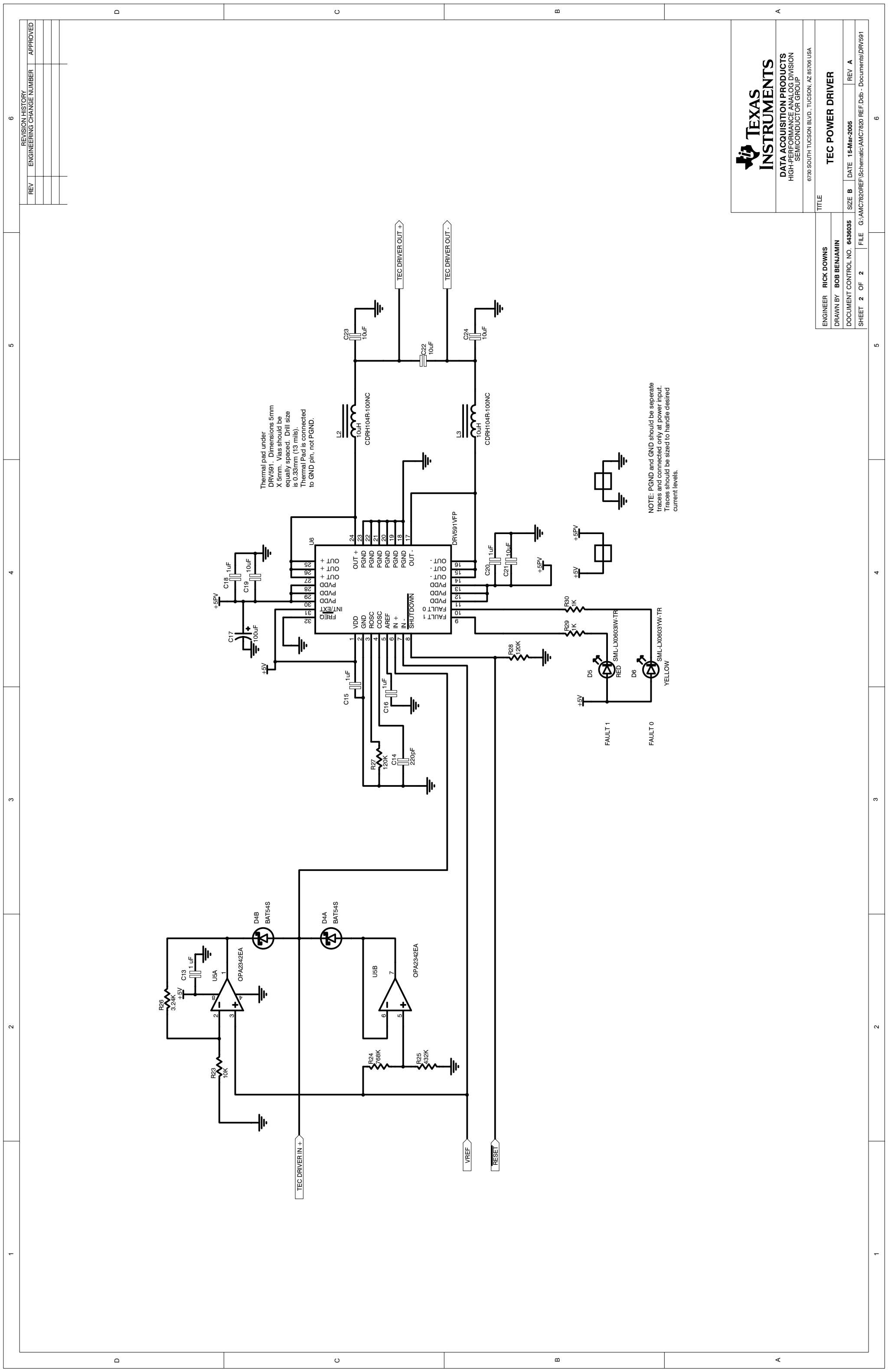
1. *AMC7820 datasheet, Texas Instruments (SBAS231B)*
2. *"Optoelectronics Circuit Collection", Texas Instruments, http://www-s.ti.com/sc/psheets/sbea001/sbea001.pdf*
3. *980nm Optilock Pump datasheet, Corning Lasertronics*
4. *"Optical Fiber Amplifiers for WDM Optical Networks", Y. Sun, A.K. Srivastava, J. Zhou, and J.W. Sulhoff, Bell Labs Technical Journal, January-March 1999, pp. 187-206.*

Schematics


A/D CHANNEL ASSIGNEMENTS
CH0 Laser Drive Control Voltage
CH1 Back Facet Monitor
CH2 TEC Drive Control Voltage
CH3 Laser Drive Current Limit
CH4 Laser Current
CH5 Thermistor Voltage
CH6 Voltage Across TEC
CH7 TEC Drive Current
D/A CHANNEL ASSIGNMENTS
DAC0 TEC Control
DAC1 Laser Drive Current Limit 0 - 1.2V - not used at this time
DAC2 Laser Control
DATA ACQUISITION PRODUCTS
AMC7820 REFERENCE DESIGN


DATA ACQUISITION PRODUCTS
HIGH-PERFORMANCE ANALOG DIVISION
SEMICONDUCTOR GROUP
TEC POWER DRIVER
ENGINEER RICK DOWNS
DRAWN BY BOB BENJAMIN
TEC DRIVER OUT +
TEC DRIVER OUT -
TEC DRIVER IN +
VREF
RESET
DRV591VFP
OPA2342EA
BAT54S
FAULT 1
FAULT 0

IMPORTANT NOTICE

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products		**Applications**	
Amplifiers	amplifier.ti.com	Audio	www.ti.com/audio
Data Converters	dataconverter.ti.com	Automotive	www.ti.com/automotive
DSP	dsp.ti.com	Broadband	www.ti.com/broadband
Interface	interface.ti.com	Digital Control	www.ti.com/digitalcontrol
Logic	logic.ti.com	Military	www.ti.com/military
Power Mgmt	power.ti.com	Optical Networking	www.ti.com/opticalnetwork
Microcontrollers	microcontroller.ti.com	Security	www.ti.com/security
		Telephony	www.ti.com/telephony
		Video & Imaging	www.ti.com/video
		Wireless	www.ti.com/wireless

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