Laser Power Supply Control for Fiber Optic Data Communications

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Fiber optics will eventually dominate the networking and communications market due to its higher bandwidth, better signal quality, immunity from electromagnetic (EM) radiation and lighter weight. However, domination can only be realized if the optical transceivers become smaller, cheaper and lower power. Most data communications systems use laser modules in high- performance optical network transceivers. Currently, fiber-optic transceiver designs have no easy means for adjusting the modulation current of the laser based upon the temperature of the laser itself and maintaining a constant light output or extinction ratio. This has led to widespread use of thermal electric coolers (TECs) to hold the laser at a constant temperature, an approach that increases the footprint, cost and power consumption of the transceiver. Eliminating the (TEC) in the transceivers while maintaining optimized performance over a wide range of ambient temperatures is key. Automatically adjusting modulation and bias current to fit individual laser diode characteristics as well as aging effects also obsoletes costly manual calibration procedures. Methods to achieve optimal laser power over temperature and time are shown in this paper with a proven reference design. The reference design includes a 2.5Gbps OC48 1310nm transmitter laser module, a differential laser driver, and an adaptive power controller with non-linear control and performance test results.

Existing Laser Solutions

Available laser solutions for long-reach applications such as telecom and/or enterprise switches use the TEC and associated control electronics to keep the laser diode at a constant temperature. This extra cooling is necessary for high power lasers designed to drive long distances. The TEC reduces the diode temperature to increase operating life at the higher power and to keep the needed modulation and bias current constant. Unfortunately, the TEC also increases the size and cost of the laser module as well as the solution complexity due to the power devices needed to control the TEC. An example of a transceiver is shown in Figure 1 and an internal schematic of a laser module is shown in Figure 2.

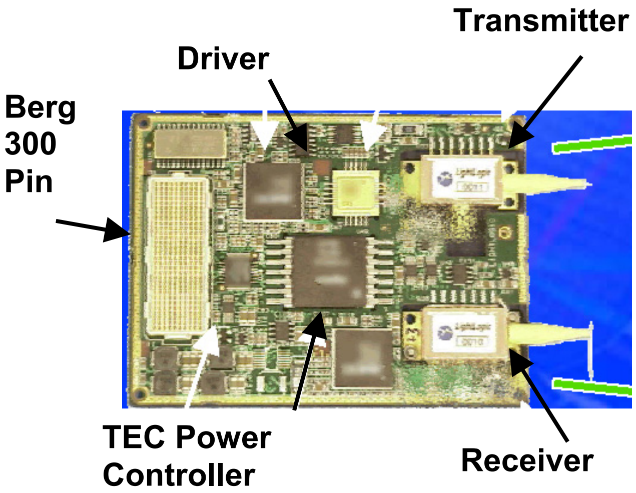


Figure 1 - Cooled Telecom/Enterprise Switch offers longer reach 2 to 40km, but larger size 4" X 3.5" and power. The size of the module is due to the physical size of the TEC and control circuit which must supply from 1A to as high as 2.5A depending on the heat generated by the laser. (Ref 1)

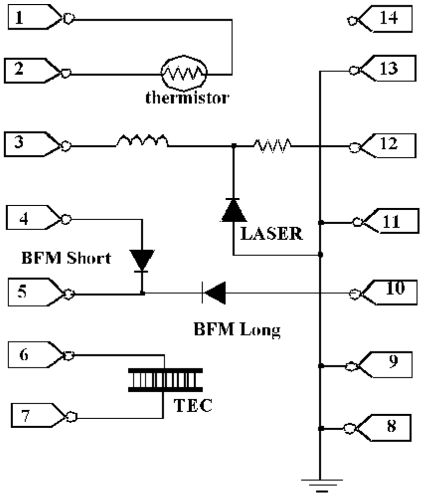


Figure 2 – Internal schematic of a transmitter laser module with a TEC for temperature control. The device includes two BFMs (Back-Faced Monitor) photodiodes, a thermister for temperature measurement and the laser diode. Advantage is longer reach. (Ref 2)

Future Laser solutions (Where is the TEC?)

Un-cooled lasers are just now starting to make inroads into telecom/switch applications. The trend toward smaller sizes is also evident in the pluggable market as governed by new standards such as Xenpack, Xpack and XFP. These require smaller un-cooled laser modules which will eventually achieve a reach of 40km. An un-cooled transceiver equivalent in performance to the one shown in Figure 1 is shown in Figure 3. The solution is smaller, uses less power and functions under the same temperature/airflow requirements as that in Figure 1. The laser module is also less expensive since there is no need for the TEC. The schematic is shown in Figure 4.

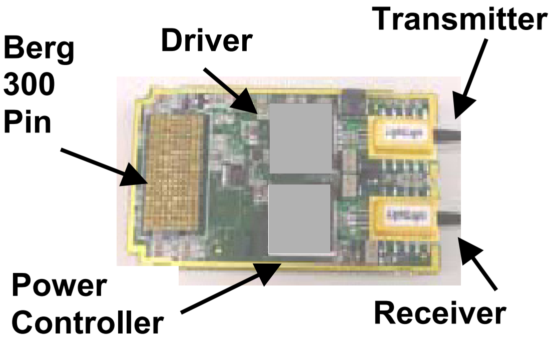


Figure 3 – Un-cooled telecom/enterprise switch offers smaller size 3.2" X 2" and lower power consumption. Reach is currently 7 to 10km with 40km in the near future. Un-cooled Lasers winning majority of sockets in Metro area and new small form factor standards (Ref 1)

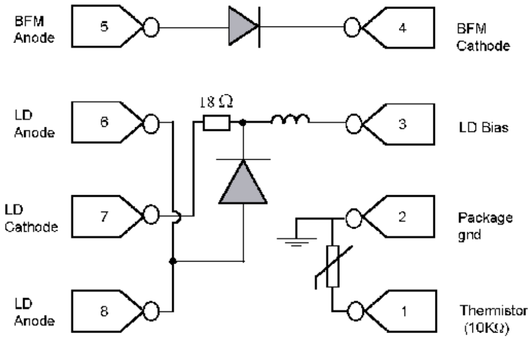


Figure 4 – Un-cooled transmitter laser module internal schematic. The device includes a BFM (Back Faced Monitor) photodiode, a thermister for temp measurement and the laser diode. Advantages include size, power, simplicity and cost (Ref 2)

A New Approach to Maintaining Laser Efficiency

Figure 5A illustrates the output light power of a laser diode versus its operating current. Depicted in the graph are typical laser diode characteristics at two different temperatures. At the lower temperature (T1), the laser requires an average bias current of IBIAS1. The modulation current needed to switch the laser between its on and off state is labeled IMOD1. The ratio of light power of its "on" state to its "off" state is referred to as the extinction ratio (ER). Ideally the laser will maintain a constant light output over its entire operating temperature range, as the receiver module is calibrated to this level. However, to maintain constant light output, the bias and modulation currents have to change over the temperature range to hold a constant ER (Figure 5B). Running the laser driver at too high an ER or modulation current results in power being wasted; whereas, operating at an ER or modulation current that is too low may result in data errors. Also, laser bias current must increase as temperature increases to keep a constant light power out.

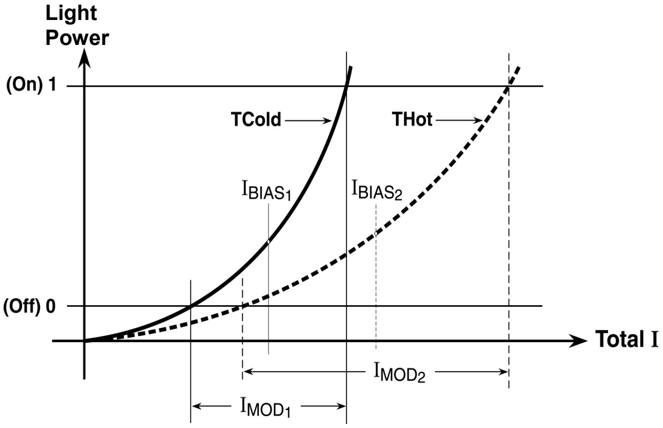


Figure 5A - Output light power of a laser diode versus its operating current. The required bias current increases to IBIAS2 when the laser is operated at a higher temperature (T_{Hot}). The laser requires a modulation current increase to IMOD2 to maintain a constant extinction ratio (ER) as in the T_{Cold} curve.

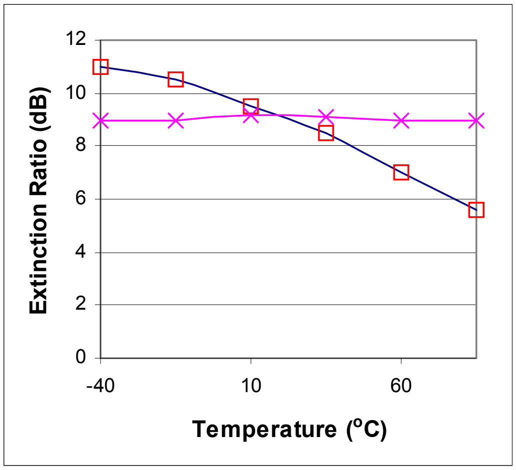


Figure 5B – Extinction ratio over temperature. The curved line (□) shows an uncompensated laser extinction ratio while the flat line (×) shows the ER after compensation. ER is constant over temperature.

A laser power controller capable of providing a variable modulation current based on a function of either the bias current or the external temperature is ideally suited to increase laser efficiency while maintaining data integrity. This ability to compensate the modulation output current optimizes and maintains the ER of the laser driver module.

Laser Module Adaptive Power Controller with Look Up Table

Adaptive thermal control of the laser has two distinct problems. The first is measuring the temperature of the laser. This is solved by measuring the bias current of the laser using the BFM. Once the temperature of the laser is determined, the second challenge is to compensate the modulation current, since each individual laser will have its own unique non-linear characteristic. An adaptive power controller (Figure 6) that includes an E^2PROM look-up table (LUT), which is programmed during setup of the transceiver, is used to generate individual compensation factors. The LUT is used to drive a modulation current source that can be configured to operate in a 0 - 10mA range for short-haul VCSEL laser applications or 0 -100mA for long-haul applications. Also, a 10-bit nonvolatile DAC is used to set the initial bias current values. An automatic power control (APC) circuit is included to maintain constant average light power through bias current control.

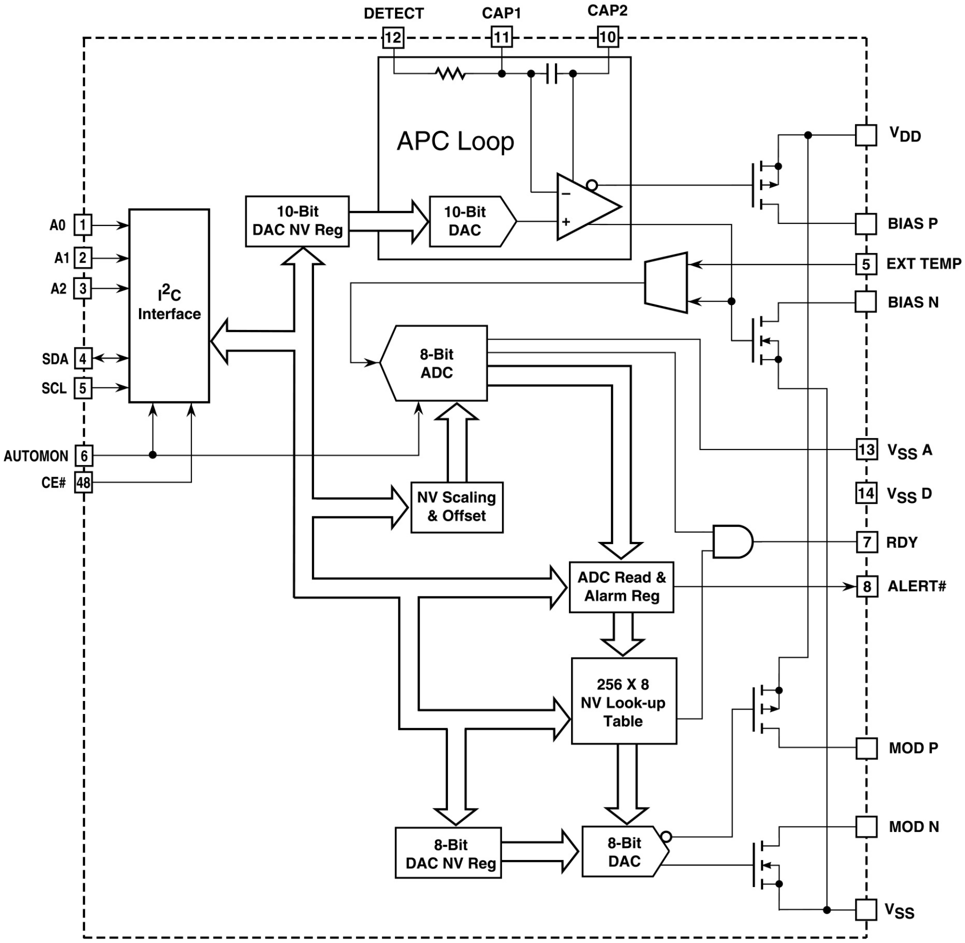


Figure 6 – The block diagram of the laser module power controller contains ADCs to monitor external temperature sensors such as thermistors integrated in laser diode modules. DACs are used to set the bias and modulation current for the laser driver and laser diode.

The integration of both bias and modulation current control eliminates the need for these functions to be placed on the laser modulating circuit, allowing the use of smaller form-factor laser drivers. This method of control is not in the high speed data path and also programmable so the controller can be used in any data rate system for most any type laser module and driver in long-haul 1300 nm, 1500nm, DWDM, DFB, Electro Absorptive or short-haul 850nm VCSELs. Using an internal digital control loop and a programmable nonvolatile compensation LUT, provides optimum adaptive power control with a minimum number of external components and also removes the need for any manual calibration of the laser control circuit. Initial calibration values are programmed through the industry standard I^2C 2-wire interface and are updated automatically over time. Most production ATE equipment or a desktop PC for testing or prototyping purposes can also control the I^2C interface. Further control of the LUT open loop analog function can be accomplished with low cost micro controllers to change the values over time.

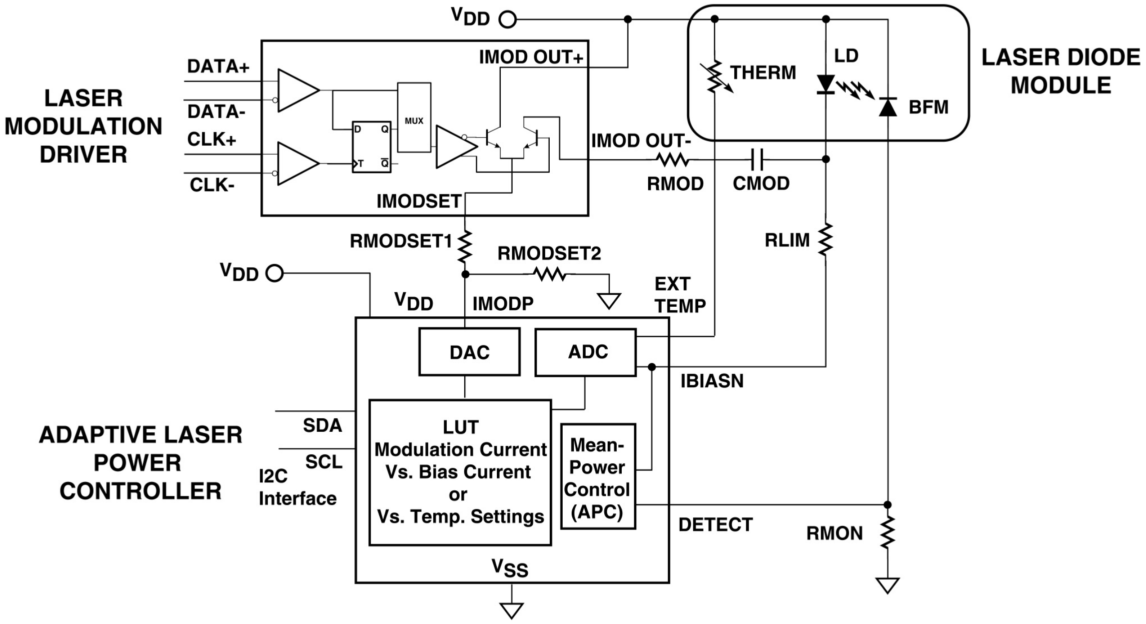


Figure 7 – The bias and modulation current control loop contains ADCs to monitor external temperature sensors such as thermistors integrated in laser diode modules. DACs are used to set the bias and modulation current for the laser driver and diode.

Bias Current — Mean Power Control

Two methods of interfacing the device with existing laser diode modules and laser driver ICs is shown in Figure 7. The bias current output (either BIASN sink or BIASP source) establishes the average power delivered to the laser diode. The output of the laser diode is separately monitored using an internal monitor diode (BFM). The output of the BFM is connected to the DETECT input. This feedback loop becomes the mean power control for the laser diode when coupled with an internal integrator in the APC loop. The output block of the mean power control is shown in Figure 8. The integration time constant is nominally 1ms. This is accomplished by using an internal 2MΩ resistor and 500pF capacitor. The time constant can be modified by adding external capacitance between the CAP1 and CAP2 terminals, and/or by adding external resistance between the DETECT and CAP1 terminals (Figure 6).

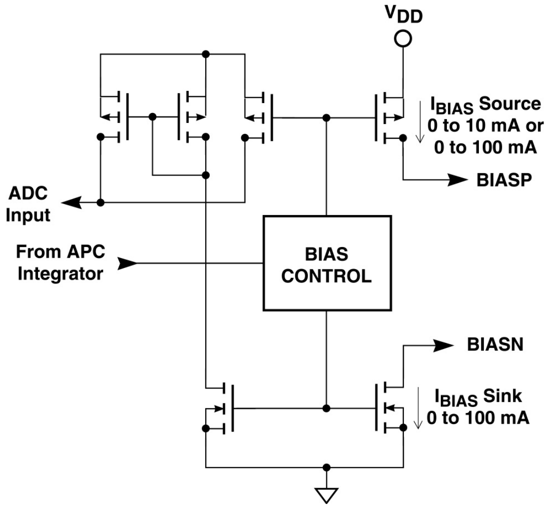


Figure 8 - Mean Power Control (MPC) Output Stage.

10-Bit Bias Control DAC

The output of an internal 10-Bit DAC biases the non-inverting input of the integrating amplifier. This provides an analog reference to the integrator that is useful for initial calibration of the laser module. The full-scale value of the DAC output is 1.5V. The DAC determines the reference voltage of the non-inverting terminal of the integrating amplifier in the mean power control loop. Associated with this DAC are a 10-Bit volatile register and a 10-Bit nonvolatile (NV) register. The content of the volatile register determines the DAC output voltage. The following relation gives the DAC output voltage:

$$OV = \frac{X}{1024} \times 1.5V$$

where X = the decimal equivalent of the 10-Bit data stored in the volatile register.

The mean power control feedback loop forces the voltage at the DETECT pin to be the same as the DAC output by driving more or less current through the laser diode.

Modulation Current — Auto-Monitor Control 8-Bit Current Sensing ADC

The laser bias current, which relates directly to laser temperature, is monitored using an internal current-sensing ADC. Using an internal auto-monitor mode, automatic adjustments are made to the modulation output currents based on the ADC output and the values stored in the nonvolatile LUT. The 8-bit output of the converter is used as the address for the LUT. The lookup table provides a precise mapping of bias current to modulation current. The input range to the ADC may be scaled and/or offset to provide maximum resolution within the appropriate conversion space. The subsequent 8-bit data output from the lookup table becomes the input for the I_{MOD} DAC. The 8-bit I_{MOD} DAC output is a programmable current in the range of 0 to 10mA or 0 to 100mA used to control the modulation current MODP and 0 to 100mA for MODN. The output block of the modulation current control is shown in Figure 9. Although the internal ADC is normally used during the auto-monitor mode, a conversion may also be performed on command via the I^2C interface.

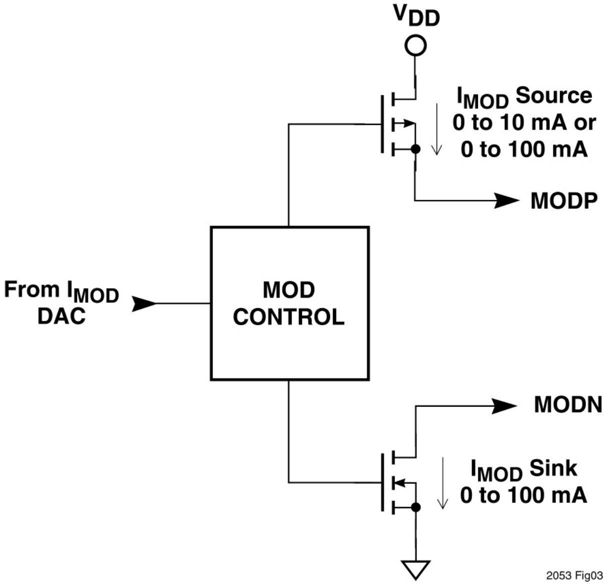


Figure 9 – IMOD Control Output Stage.

Look Up Table (LUT)

A 2k-Bit (256 x 8) memory array of internal E^2PROM comprises the internal LUT. In the auto-monitor mode, the contents of the array represents the transfer function between the ADC output and the modulation current. Using a LUT to implement this function allows arbitrary functions, and even nonlinear relations, to be easily realized. Also, the use of a LUT allows each device to be programmed to optimize overall module operation. The LUT is required for any laser not using a TEC and/or requiring a correction factor as the laser ages.

8-Bit Current Output DAC

The 8-bit DAC sets the modulation output current. Associated with this DAC are an 8-bit volatile register and an 8-bit nonvolatile (NV) register. The contents of the volatile register determines the DAC output current. The DAC output current is given by the following relation:

$$OC = \frac{X}{256} \times 100mA$$

where X = the 8-bit data stored in the volatile register.

Upon device power-up, the volatile register may be loaded with all zeroes or it may be loaded from the contents of the 8-bit nonvolatile register. Access to the 8-bit volatile register is obtained via the I^2C interface.

ADC Scaling and Offset

The ADC can be customized to monitor a particular range of bias current by programming an internal configuration register. Depending on the laser diode application, the IBIAS maximum current option is set to either 10mA or 100mA. These combinations of scales and offsets allow the resolution to be maximized over a given range of current. For example, if the bias current is known to be in the range of 30mA to 70mA, the scale can be set to maximize the resolution of the ADC. This allows optimization for each type of laser diode. The ALERT pin is driven low whenever the bias current increases beyond a predefined nonvolatile threshold programmed into the laser power controller. This can be used to monitor laser stability, predict laser failure and/or enable an alert condition for the ADC to shut down the bias current to prevent laser diode damage.

An EXT TEMP pin allows the input of the internal ADC to be driven from an external device, rather than a mirrored version of the bias current to directly measure laser diode temperature. The scale and offset features of the ADC input can be used to center this current and maximize the full range of the LUT. The converted value of the current entering this pin is used as the address of the E^2PROM LUT. In this configuration, the modulation current can be controlled by temperature rather than the bias current.

OC48(2.5Gbps) Example Application

An example application using a 2.5Gbps OC48 1310nm transmitter is shown in Figure 10B containing the laser power controller. Figure 10A shows the laser driver and laser transmitter module. The laser module is for short reach single mode applications at a nominal data rate of 2.5Gb/s and is pin Compatible with OC48 IR/LR applications. The laser module (Figure 4) is packaged in a standard 8-pin ceramic MiniDil platform employing internal one-piece fiber alignment technology coupled with a VHT MQW laser diode. The 5mW laser diode has been specifically developed for operation over a wide temperature range. The module contains an internal back facet monitor diode (InGaAs PIN BFM), suitable for mean power control. It also contains an internal 10kΩ thermistor for temperature monitoring purposes. The laser driver is a single +3.3V or +5V supply device for SONET/SDH applications up to 3.125Gb/s. Data and clock inputs accept differential PECL signals. External resistors set a wide range of bias and modulation currents for driving the laser. For this application, the adaptive laser power controller has replaced the fixed resistor settings for the modulation and bias current settings. The laser driver provides the raw modulation current while the power controller provides the laser's bias current, photodiode loop closure (constant light output control) and modulation current control via the laser driver's MODSET pin. The power controller functions together with the laser driver and module to provide a complete 2.5Gb/s Optical Transmitter solution.

Figure 7 displays a simplified schematic employed by the laser module, laser driver modulation interface and the bias/modulation power controller. Using the laser module's photodiode as a means of monitoring the optical output power, the controller's DETECT pin senses the voltage drop caused by the photodiode current across RMon, adjusting the laser current into the BIASN pin accordingly. The steady state voltage at the DETECT pin is at a preprogrammed non-volatile setting of 0-1.5V. The value of RMon is chosen so the voltage drop seen at the DETECT pin is 0.75V for the nominal output current of the photodiode with the laser biased on:

$$\mathrm{RMon} = \frac{0.75}{I_{PD}}$$

For this laser module (Figure 4), a 4.7kΩ resistor is used to ensure an adequate voltage is developed when the photo-detector gain is minimum. A resistor inserted between the laser cathode and the power controller's BIASN pin ensures the laser's absolute maximum current rating is not exceeded:

$$\mathrm{RLim} = \frac{5 - \mathrm{Vf}}{\mathrm{ITH} + 0.060}$$ Where Vf is the forward voltage of the laser diode

A 30Ω resistor is used in conjunction with the internal 18Ω resistor in the laser module.

The modulation current is indirectly controlled by terminating the MODP output into a low value resistor RMODSET2 (R29, 220Ω) and summing this node via RMODSET1 (R1, 2.5kΩ) into the laser driver's MODSET pin. The value of RMODSET1 is chosen to maximize the modulation current while the power controller's MODP output current is programmed in the non-volatile LUT to obtain a suitable 'bucking' voltage that sets the modulation current for the optimal modulation current over temperature, laser diode aging and other factors that might otherwise result in a less than the ideal laser performance. For this particular laser module, the data in the LUT was determined from data taken at several different temperatures and bias currents. However, the data can also be non-linear to optimize performance at distinct operating conditions. The data can be entered manually into each memory location with a MS-Windows^{TM} based graphical user interface (GUI) (Figure 14), imported into the GUI through an Excel spreadsheet or loaded directly into the device through a micro controller or other I^2C device.

The laser power controller's MODP pin is used to set the laser driver's MOD output current and therefore it is necessary to know the laser driver's modulation current versus the current into its' MODSET input. The MODSET input current of the laser driver is a fraction of the laser driver MOD output current, so the transfer function between the two is obtained from the laser driver's data sheet. However, the modulation current required to produce the optimal ER (or acceptable Eye diagram, Figure 18) varies from laser to laser and from one temperature to another. To acquire the data for the LUT, the following information is needed from the laser manufacturer data sheet or from testing the ER of the laser, the laser threshold current I_{TH} (logic '0') and the drive current above I_{TH} (logic '1'). This requires setting different values in the LUT for the different input temperatures or bias currents. The procedure requires an environmental chamber and the necessary equipment to measure the laser output power to ensure the MOD output current changes correctly as does the external temperature or the bias current. The LUT data contents for this application are available upon request.

If external temperature control is used to address and retrieve the contents of the LUT, Figure 10A shows an example using a temperature sensor (U2) that delivers a current proportional to absolute temperature. The current ISET into the EXT TEMP pin is given by the following equation:

$I_{SET} = (T \times 227\mu V/^{O}K)/R_{SET}$ where T = Temp in degrees Kelvin, R_{SET} is R3 in Figure 10A.

In the configuration shown, a value of 210Ω for RSET(R3) yields a current of 295µA at 0°C and 387µA at 85°C.

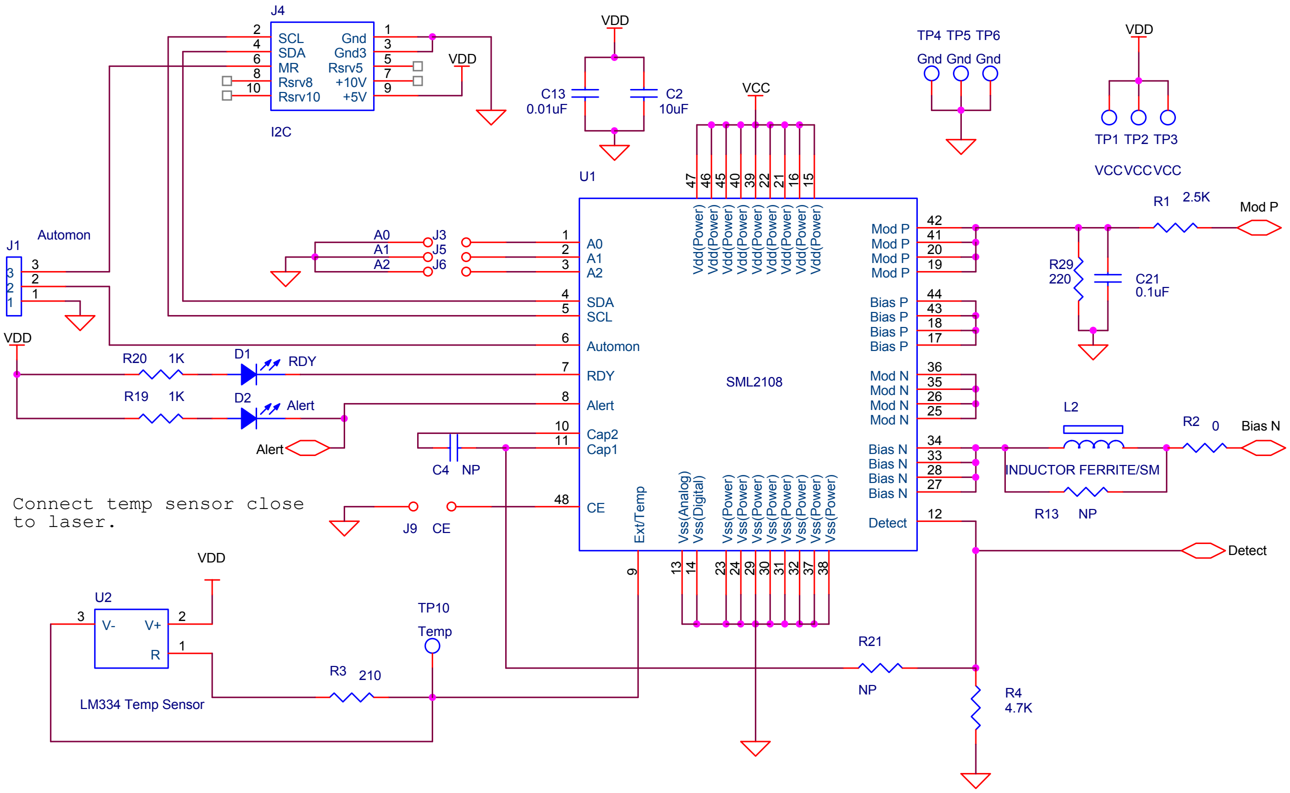


Figure 10A – Adaptive Laser power Controller Reference Design Schematic.

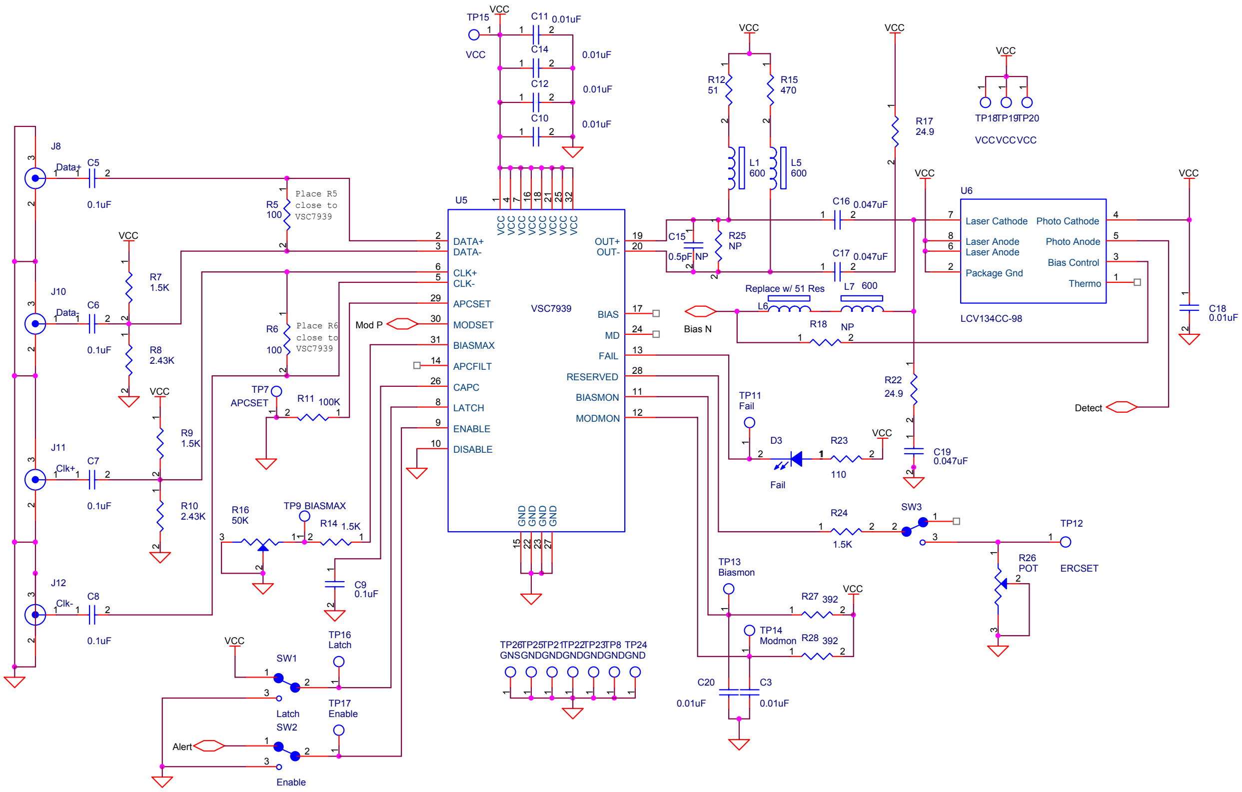
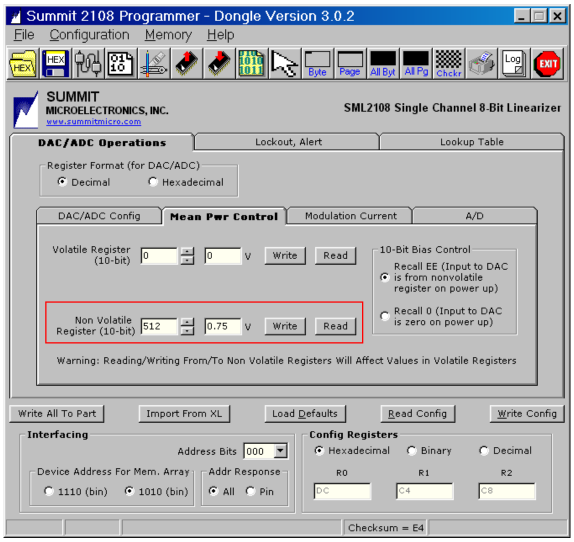


Figure 10B - Laser Driver and Module Reference Design Schematic

Programming GUI

The following figures were generated using the OC48(2.5Gbps) reference design, a Windows compatible GUI and SMX3200 I^{2}C Programmer.



Register Format (for DAC/ADC) ● Decimal ○ Hexadecimal

Volatile Register (10-bit) 0 | 0 V

10-Bit Bias Control
● Recall EE (Input to DAC is from nonvolatile register on power up)
○ Recall 0 (Input to DAC is zero on power up)

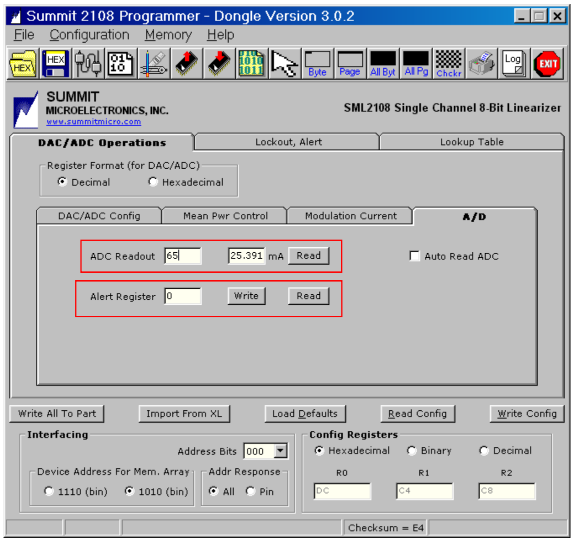
Non Volatile Register (10-bit) 512 | 0.75 V

Warning: Reading/Writing From/To Non Volatile Registers Will Affect Values in Volatile Registers

Interfacing
Address Bits 000
Device Address For Mem. Array ○ 1110 (bin) ● 1010 (bin)
Addr Response ● All ○ Pin

Config Registers ● Hexadecimal ○ Binary ○ Decimal
R0 DC
R1 C4
R2 C8

Checksum = E4



Register Format (for DAC/ADC) ● Decimal ○ Hexadecimal

ADC Readout 65 | 25.391 mA

☐ Auto Read ADC

Alert Register 0

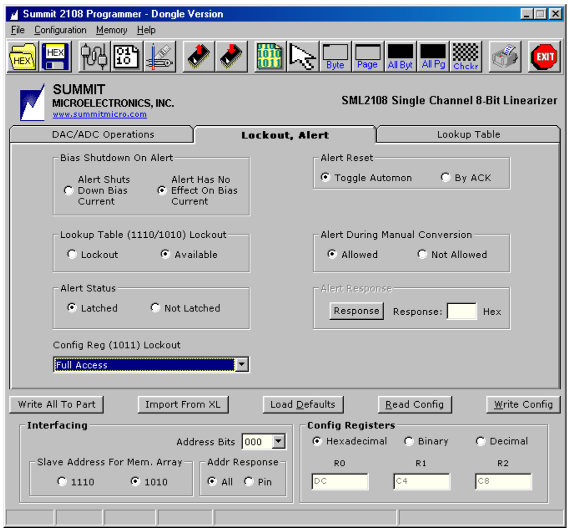
Interfacing
Address Bits 000
Device Address For Mem. Array ○ 1110 (bin) ● 1010 (bin)
Addr Response ● All ○ Pin

Config Registers ● Hexadecimal ○ Binary ○ Decimal
R0 DC
R1 C4
R2 C8

Checksum = E4

Figure 11: Setting the DETECT Pin Servo Voltage (Photodiode Current Times R4).

Figure 12: Measure the Resulting Bias Current through the ADC, Set the Alert limit



SML2108 Single Channel 8-Bit Linearizer

Bias Shutdown On Alert
○ Alert Shuts Down Bias Current
● Alert Has No Effect On Bias Current

Alert Reset
● Toggle Automon
○ By ACK

Lookup Table (1110/1010) Lockout
○ Lockout
● Available

Alert During Manual Conversion
● Allowed
○ Not Allowed

Alert Status
● Latched
○ Not Latched

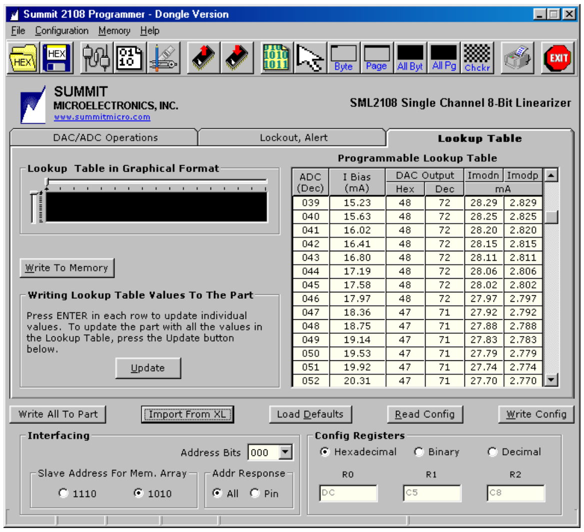
Alert Response
Response: Hex

Config Reg (1011) Lockout
Full Access

Interfacing
Address Bits 000
Slave Address For Mem. Array
○ 1110
● 1010
Addr Response
● All
○ Pin

Config Registers
● Hexadecimal
○ Binary
○ Decimal
R0 DC
R1 C4
R2 C8

Figure 13: Setting Alerts and Shutdowns.



SML2108 Single Channel 8-Bit Linearizer

Lookup Table in Graphical Format

Programmable Lookup Table

ADC (Dec)	I Bias (mA)	DAC Output		Imodn	Imodp
		Hex	Dec	mA	
039	15.23	48	72	28.29	2.829
040	15.63	48	72	28.25	2.825
041	16.02	48	72	28.20	2.820
042	16.41	48	72	28.15	2.815
043	16.80	48	72	28.11	2.811
044	17.19	48	72	28.06	2.806
045	17.58	48	72	28.02	2.802
046	17.97	48	72	27.97	2.797
047	18.36	47	71	27.92	2.792
048	18.75	47	71	27.88	2.788
049	19.14	47	71	27.83	2.783
050	19.53	47	71	27.79	2.779
051	19.92	47	71	27.74	2.774
052	20.31	47	71	27.70	2.770

Writing Lookup Table Values To The Part

Press ENTER in each row to update individual values. To update the part with all the values in the Lookup Table, press the Update button below.

Interfacing
Address Bits 000
Slave Address For Mem. Array
○ 1110
● 1010
Addr Response
● All
○ Pin

Config Registers
● Hexadecimal
○ Binary
○ Decimal
R0 DC
R1 C5
R2 C8

Figure 14: Generating the MOD Output Current in the Lookup Table (LUT).

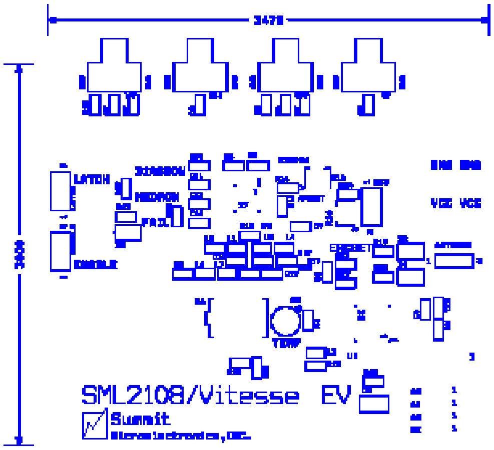


Figure 15 - OC48 Reference Design Top Silkscreen.

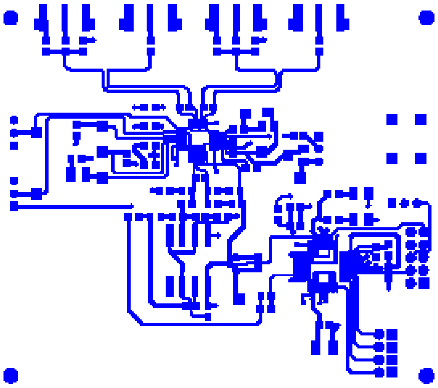


Figure 16 - OC48 Reference Design Top Copper.

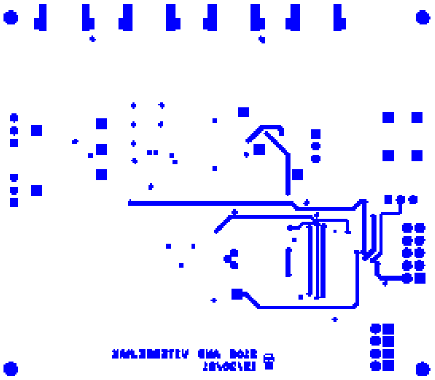
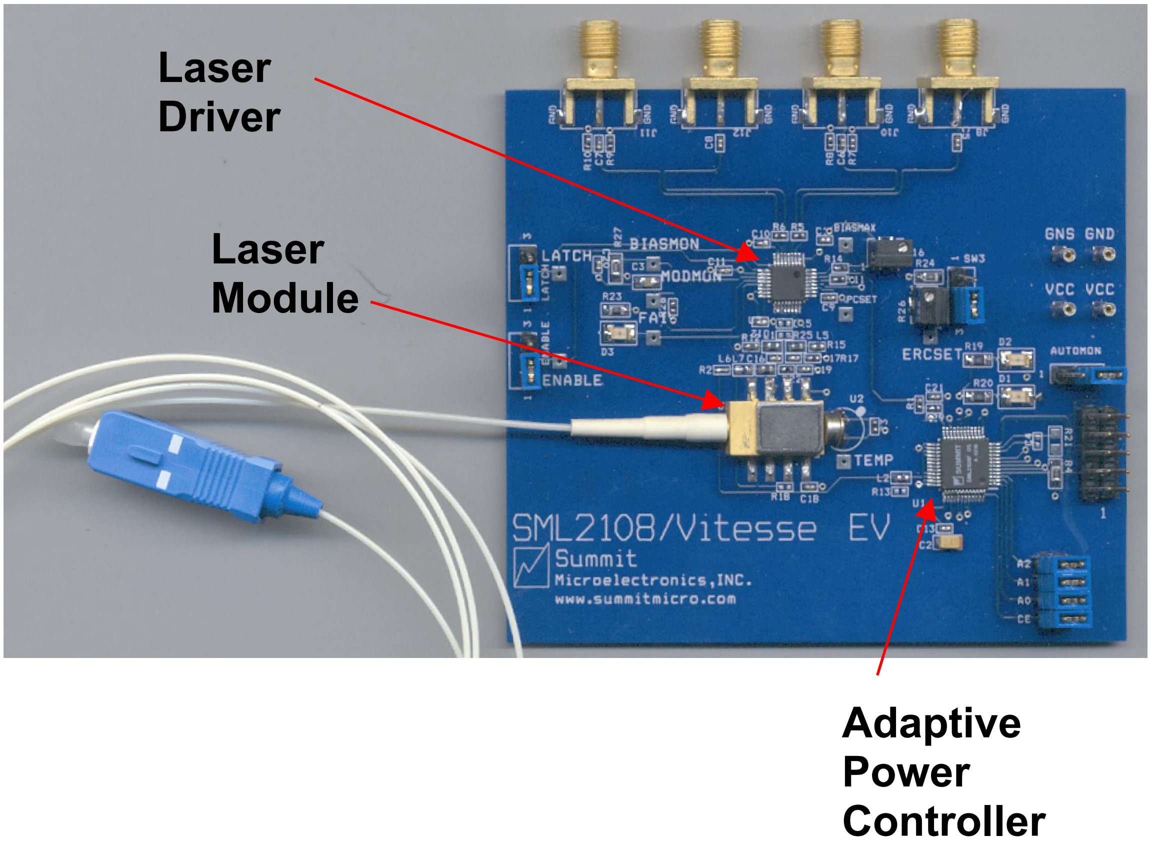


Figure 17 - OC48 Reference Design Bottom Copper.



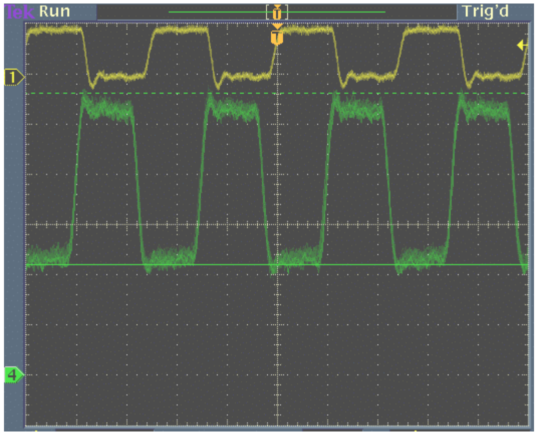
Un-Cooled OC48 Transmitter Reference Design

–Automatically corrects and maintains optical output power over temp
–Eliminates performance compromises associated with un-cooled lasers
•Programmable adaptive laser power controller
–Compensates laser tolerances with a digital control loop containing a programmable non-volatile LUT
–Interfaces with standard laser drivers and laser modules
–Active feedback loop calibrates and controls the mean power and ER over temperature
•Production process simplified
–Dual-loop control detects and compensates for each laser's particular temperature characteristics
–Design is more suitable for large-volume production and lowers costs

Bias and Modulation Current Vs Temperature

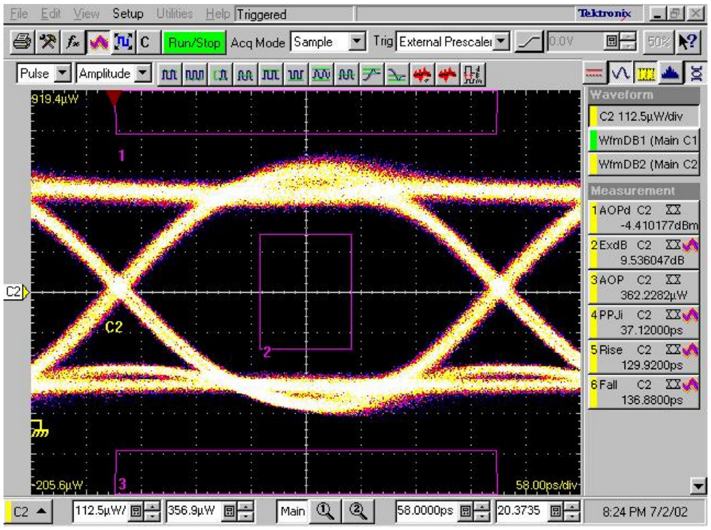
0°C - 10mA/Div
Bias = 14mA – Average level
Mod = 17mA - Amplitude

25°C - 10mA/Div
Bias = 19mA
Mod = 31mA



85°C - 10mA/Div
Bias = 22mA
Mod = 38mA

- Modulation current amplitude increases as average bias current level increases
- Maintains Fixed Extinction Ratio



Acq Mode Sample
Trig External Prescaler
0.0V
50%

C2 112.5µW/div
WfmDB1 (Main C1
WfmDB2 (Main C2

1 AOPd C2 -4.410177dBm
2 ExdB C2 9.536047dB
3 AOP C2 362.2282µW
4 PPJi C2 37.12000ps
5 Rise C2 129.9200ps
6 Fall C2 136.8800ps

C2 112.5µW/ 356.9µW
58.0000ps 20.3735

Figure 18 – Eye Diagram AC-coupled to Laser, retimed, VSS=+3.3V, 85°C, OC-48, PRBS23

Conclusions

This reference design represents a major change in the way fiber-optics transceivers will be applied in the future. Inherent manufacturing tolerances introduce variations of performance in laser diodes. These variations, combined with parametric changes over the laser's extreme temperature range and laser aging, call for an efficient compensation solution. With a minimum number of external components, an adaptive power controller designed to compensate for these tolerances uses a digital control loop and a programmable nonvolatile compensation look-up table. The controller makes this possible with an active feedback loop used to calibrate and control the mean and modulation power of high speed, high power laser diodes. This method automatically corrects and maintains the optical output both over temperature variations and aging effects in the laser, eliminating some of the performance compromises associated with open-loop control. The production process is also simplified as the dual-loop control detects and compensates for each laser's particular temperature characteristic, leading to a design that is more suitable for large-volume production and lower costs.

References:

1. Intel Developer Forum Spring 2002, "Emerging Standards and Multi–Source Agreements in the 10Gb/s Optical Market Segment", Gary Wiseman, Marketing Director Intel Optical Platform Division

http://seminar2.techonline.com/~intel22/jun1902/

2. Nortel Networks, LC25EW 2.5 Gb/s Etalon Locked Buried HET Laser Datasheet, LCV134CC-98 Fiber Optic Transmitter Datasheet,
http://www126.nortelnetworks.com/

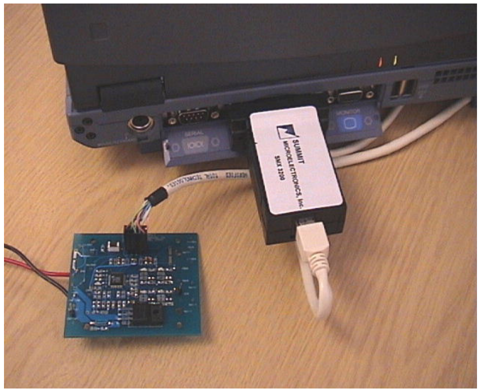
3. Vitesse Semiconductor Corporation, VSC7939 SONET/SDH 3.125Gb/s Laser Diode Driver with Automatic Power Control Datasheet
http://www.vitesse.com/

Total Solution Benefits

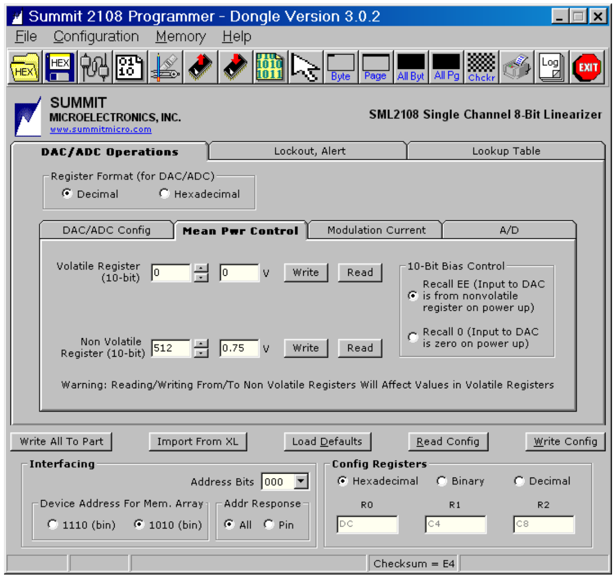
- Maintains Laser Diode Mean Power and Modulation Control for Constant ER Over Temp
- Adaptive Modulation Control
  - Eliminates need for external cooler, temp compensated setting resistors, and manual calibration
- Automatic Power Control (APC)
  - With Non Volatile Calibration
- Alarm circuitry
  - Provide interrupt when laser limits are exceeded
- In system programming
  - Eliminates manual calibration
  - LUT can be updated over time - Aging

Development Tools - Programmable Analog

- Programming Cable Connects PC Printer Port and Target System
- 2 Wire I^2C Serial Bus for all Programming



- Reduces prototype time
- Allows system optimization



SML2108 Single Channel 8-Bit Linearizer

Register Format (for DAC/ADC): ● Decimal ○ Hexadecimal

Volatile Register (10-bit): 0 | 0 V

Non Volatile Register (10-bit): 512 | 0.75 V

10-Bit Bias Control:
● Recall EE (Input to DAC is from nonvolatile register on power up)
○ Recall 0 (Input to DAC is zero on power up)

Warning: Reading/Writing From/To Non Volatile Registers Will Affect Values in Volatile Registers

Interfacing: Address Bits 000

Device Address For Mem. Array: ○ 1110 (bin) ● 1010 (bin)

Addr Response: ● All ○ Pin

Config Registers: ● Hexadecimal ○ Binary ○ Decimal

R0: DC | R1: C4 | R2: C8

Checksum = E4

- Programmed in-system Using MS Windows® Compatible GUI Development Tools
- GUI Outputs Hex File

- Simplifies production process