Software Enabled Control System for Lasers

Introduction

Semiconductor lasers (laser diodes) are currently used in numerous product applications. Some of these applications include transceivers, which are used to send and receive information in an optical communications channel, sensors and instrumentation, consumer products such as optical storage (DVDs) and, military applications. In all applications, designers are challenged with problems related to performance variations of the laser such as manufacturing variability, temperature effects and aging degradation. Various approaches have been utilized to stabilize laser operation: Analog controllers, analog-digital circuit controller combinations, cooler/heaters, manual adjustments, extensive calibration testing, and digital circuit controllers with look-up tables.

The CEYX control solution consists of circuits and methods used to control laser diodes and associated transceiver components. The control of the laser is carried out with a Software Enabled Control System, which is at the forefront of developments in the field of Controls and Computer Science. The software-enabled system allows instant adaptation of the controls for any type of diode laser while producing superior results in the accuracy of the operating points for the parameters that determine laser performance. The software-enabled system is adaptive in that it compensates for aging, operating temperature and laser / device manufacturing variations. The result is precise and consistent optical power modulation amplitude and other parameters over temperature during laser life. The architecture of the Software Enabled Control System is highly efficient and modular and can be embedded in single chip microcontroller for very small size, low power and cost efficient solutions.

Laser Device Characteristics

Semiconductor lasers are one of the key components of an optical transceiver whose function is to convert electrical signals to optical signals.

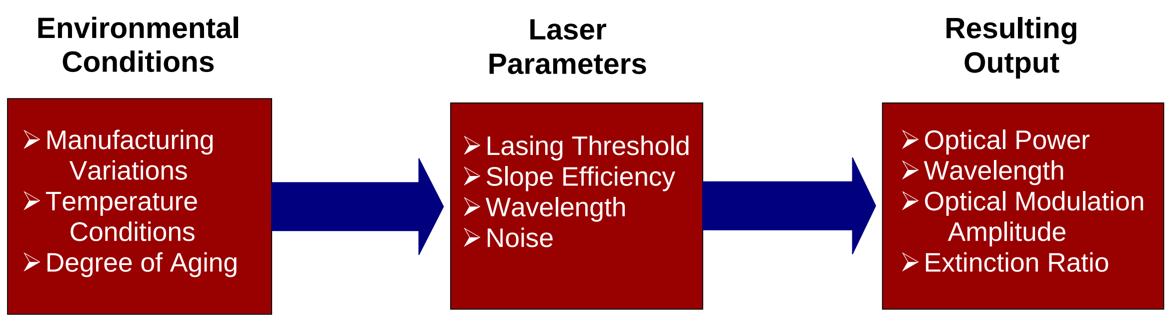

Figure 1: Laser Performance Parameters

Illustrated in Figure 1 are some of the challenges associated with laser diodes. Environmental conditions related to manufacturing variations, temperature conditions and aging of the laser affect laser operation and cannot be avoided. Environmental conditions affect inherent characteristics of the laser, which in turn determine the quality of the output obtained from the laser.

Since environmental conditions cannot be avoided, laser parameters must be controlled in such a manner that the required output such as optical power and, wavelength is obtained. Other output requirements are average optical power (AOP), optical modulation amplitude (OMA) and extinction ratio (ER). AOP is the operating point for the laser which accounts for the average of the power obtained with bias and modulation currents applied. OMA is the difference between optical power between a logical high output and a logical low. ER is a logarithmic relationship between the logical high optical power and the logical low optical power.

As an example of how environmental conditions affect laser parameters and the laser output, consider Figure 2 below.

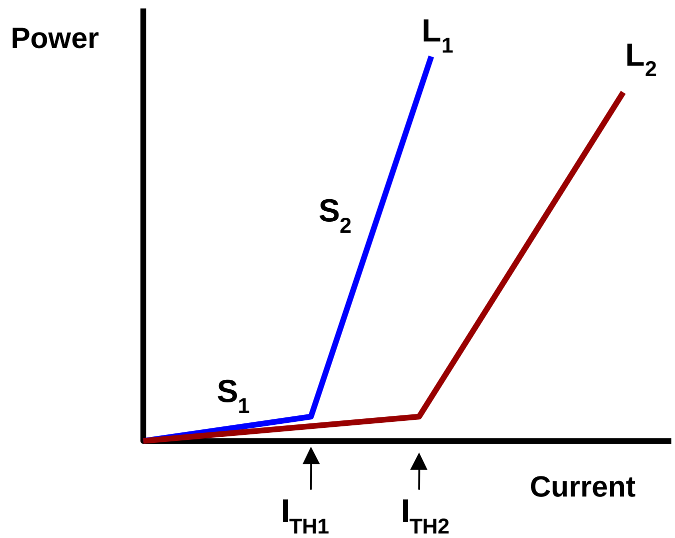

Figure 2: Laser Diode Characteristics

The graph represents laser characteristics for optical power output versus laser current. Turning our attention to the curve labeled L_1, which represents the laser characteristic at temperature T_1, we can see that the graph contains two regions: S_1 is the characteristic of the laser before it operates in lasing mode (often referenced as the LED phase) and, S_2 is the portion of the characteristic after the laser diode performs as a laser (often referenced as the lasing phase). The threshold current I_{TH1} determines the separation between the two regions. The threshold characteristic is typical of all lasers including Fabry Perot, MWQ, VCSEL and others. In order to utilize the laser, there is the need to first drive the laser with an amount of current beyond I_{TH1} from a bias current source in order to ensure operation in the laser region. After this is done, the laser is then driven with a modulation current generated by a second current source. Variation of the modulation current source versus time causes a proportional variation of the optical power versus time. The transmitted and useful laser optical power is dependent on how the modulation is current source is varied.

As the figure shows, characteristic L_2 represents the laser behavior at temperature T_2. Therefore, if the laser is set to operate at temperature T_1, then a change in temperature to T_2 can mean that the laser will not operate anymore. For example, suppose the total applied current at T_1 was I_{L1}, producing an optical power of P_1. If the temperature then changes to T_2, the amount of output optical power is severely reduced to P_2, and in this case, the laser does not work anymore as a laser. Research in Naval Laboratories has found that any laser operating at or near threshold will be limited in switching speed and the optical power will exhibit a high amount of noise.

The foregoing discussion illustrates the challenges laser system designers face in dealing with laser characteristic changes caused by temperature effects. In addition, similar changes to the laser characteristic are caused by manufacturing variations and by aging of the laser. Other lasers such as VCSELs display a significant curvature of the section S_2 of the characteristic with increases in temperature. Other factors include stability of the wavelength and preservation of modulation signal amplitude with aging. Furthermore, cost and size constraints in present day products place additional restrictions on the solutions, thus impacting performance.

Traditional Laser Control Approaches

Closed loop analog controllers set laser operation using a signal from a photodiode sensor. The photodiode sensor detects the optical power from the laser and produces an output current proportional to the optical power from the laser. The analog circuit controller then adjusts the laser power according to a predetermined value as determined by a scaling of associated circuit currents and voltages. The so-called “dual loop” controllers are analog controllers where two different mechanisms are used to set the laser operation. Two parameters need to be set for laser operation: bias current to set the laser in laser operation mode and modulation current used to set the amount of laser power corresponding to the amplitude of the optical signal required for data transmission. The photosensor signal represents average laser power, which is used to set the bias current for the laser. The modulation current of the laser is then set with a scaling factor usually by a scaling factor determined by external resistors.

Disadvantages of the analog controller are that the initial laser bias and modulation characteristics of the laser are part variation dependent, thus there is the need to perform an initial adjustment at the factory to compensate for the variation in order to set the correct data point. Since the system is implemented with an analog approach this requires additional components such as resistors or potentiometers (often manual) to set the current. This approach will add cost and increase the size of the solution. In addition, to compensate for temperature changes, the analog controller uses the photosensor signal, another signal from a reference circuit and, a scaling factor. The scaling factor is fixed and represents an assumption about how the modulation current should be adjusted for temperature changes. This temperature compensation approach introduces a significant error in the laser power setting for temperature changes. This problem is especially significant for lasers that are power efficient (high slope efficiency). Other issues with this approach have to do with the low amount of design leverage from one product generation to another. New products will require new customized circuits that will need new designs.

Analog-digital circuit combination controllers are essentially analog controllers, which are assisted by A/D and D/A data converters. The data converters are used to perform adjustments to the set point of the laser in a way that manual adjustments are minimized. The disadvantages of this approach are similar to the analog controller approach.

Digital circuit controllers with look-up tables provide the advantage of some degree of flexibility and leverage due to the digital control. However, look-up tables have disadvantages. If an assumption is made that all lasers used in the product exhibit the same characteristics, performance is compromised due to significant errors in the setting of the operating parameters, the result of inherent laser variability. If each individual laser is characterized as is required for some critical applications, costs increase substantially. In both cases there can be a significant degradation due to aging and in performance due to interpolation inaccuracies when using tables to account for temperature changes.

Another approach utilizes tone control. A tone is a small high frequency signal applied to the modulation. This signal causes the optical power to reflect the signal riding on top of the actual signal being stabilized. The tone signal is detected and, by understanding the transfer functions of the tone, circuits can then determine how the modulation changes with temperature. The tone control has the disadvantage of adding noise to the modulation signal which decreases signal to noise ratio. Adding circuits to inject a tone and to filter and amplify the output to detect the tone considerably increases design complexity and cost.

The CEYX Solution

The CEYX solution consists of three elements:

- Software Enabled Control System
- Embedded Control Algorithms
- Laser Control Hardware

Software Enabled Control System

The Software Enabled Control System is a key element of the technology developed by CEYX to control Electro-Optic systems and components. The unique and special characteristic of the Software Enabled Control System is that it allows changes in the operating modes of the control system. A change in the operating modes means that the software can be made to control a system in a variety of manners and with different algorithms. The Software Enabled Control System is also re-configurable. A change in configuration allows the control of any laser, photodiode, driver, sensor, etc. instantly after the configuration is completed. These operating modes and configuration of the Software Enabled Control System are programmable by loading the appropriate parameters and data in a special embedded memory location called System Configuration. Examples of Configuration data are parameters for embedded equations and models, parameters for the laser diode, transfer function for the laser driver chip, photodiode sensor parameters and temperature sensor parameters.

There are three methods used to program the System Configuration:

1) The first method is to load all necessary data into an embedded MCU in ROM, Flash or other memory at the MCU factory. This approach is most useful for very low-cost applications with relatively stable designs.
2) A second method is to program the system configuration during the manufacturing test of the product using the control system. System configurations are loaded through the serial I/O from a computer during manufacturing test.
3) For truly advanced networks, a third method is to have a Host Computer in an installed system perform the initialization of the System Configuration. This approach is most useful in Network applications when there is uncertainty regarding a transceiver's Configuration requirements. It also is a means to allow the Host Computer to re-configure the transceiver when in service, or for applications where the control system is required to dynamically change over time. Figure 3 illustrates the configuration method for a Software Enabled Control System when a Host Computer carries out the programming. To configure the control system for a new laser application, a Host Computer retrieves configuration data from its database and places the appropriate information into a Configuration memory, which is part of a Software Enabled Control System. Once the configuration is complete, the Software Enabled Control System is able to operate on its own without any assistance from the Host Computer in the most optimal manner to the System Under Control.

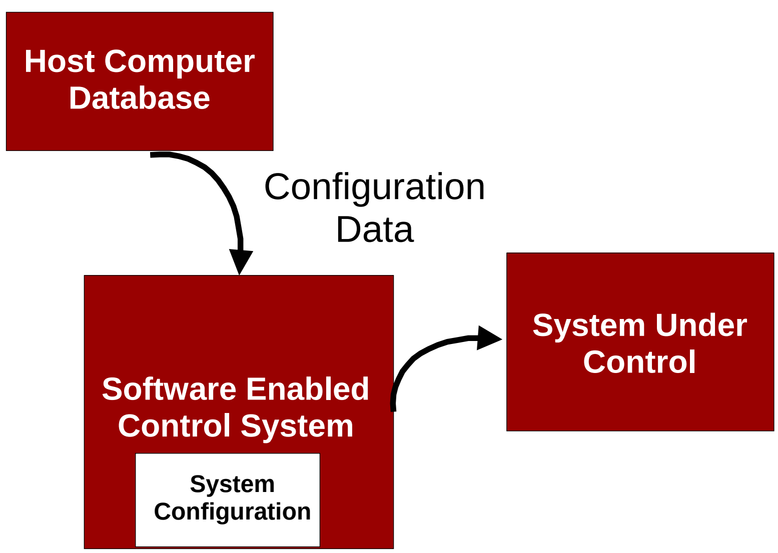

Figure 3: Software Enabled Controls System

Embedded Control Algorithms

The Embedded Control Algorithms consist of a suite of servo algorithms and methods implemented in a variety of control processes. The key components used specifically for laser control are:

- Servo Control Method
- Average Optical Power Control Servo
- Optical Modulation Amplitude and Extinction Ratio Control Servo
- Transceiver Nonlinear Models
- CEYX Microdetector
- Expert threshold detector

The Servo Control Method

The design elements of a servo cycle are: an active component requiring control (forward path), closed-loop feedback path which includes sensors, decision criteria for performance modification, followed by modification of the active component and, continuous repetition of the cycle. The significant advantages of Servo Control for the laser are:

- Very high levels of precision are achieved because the laser parameters are set to levels allowed by digital processes and digital hardware
- Component variation is compensated for with system calibration
- Because the laser is controlled by a continuous closed loop basis, the parameters are automatically set upon power-up to the appropriate set points according to the System Configuration
- Servo action performs automatic compensation
- Because the Servo is implemented in a digital program, it is possible to implement complex models for any of the components used in the transceiver. For example, nonlinearities and temperature models can be rapidly updated and thoroughly characterized
- Design changes to the parameter settings or responses can be made anytime by changing the System Configuration without any hardware changes
- Optimal dynamic response for laser parameters is achieved because the servo operates in a real-time mode

Shown in Figure 4 below is a representative model for servo control of a laser output.

The various elements are:

- The forward path consists of a Servo Controller, which is a mathematical model appropriate for the laser system of interest, a laser drive circuit transfer function, and the laser. The mathematical model determines the dynamic response of the servo control system in order to achieve the required laser output. Where appropriate, the Servo Controller may also contain a digital filter to achieve desired output dynamic response.
- The feedback path contains one or more sensors, sensor signal detector, and signal processor. Photodiode and/or temperature sensors are generally used to set monitor the laser power output and temperature conditions. Some systems include other types of sensors such as wavelength sensors, and heater/coolers. In order to properly use the Sensor (s) information after it is detected with the precision required by the application, the Signal Processor interprets the sensor(s) information.
- Servo input. The SET input determines the set point for the required OUTPUT. The controlled parameter may be for example laser power or wavelength. A comparison is made between the SET input and the FEEDBACK from the sensor(s) and any error is compensated by the CEYX Control System.

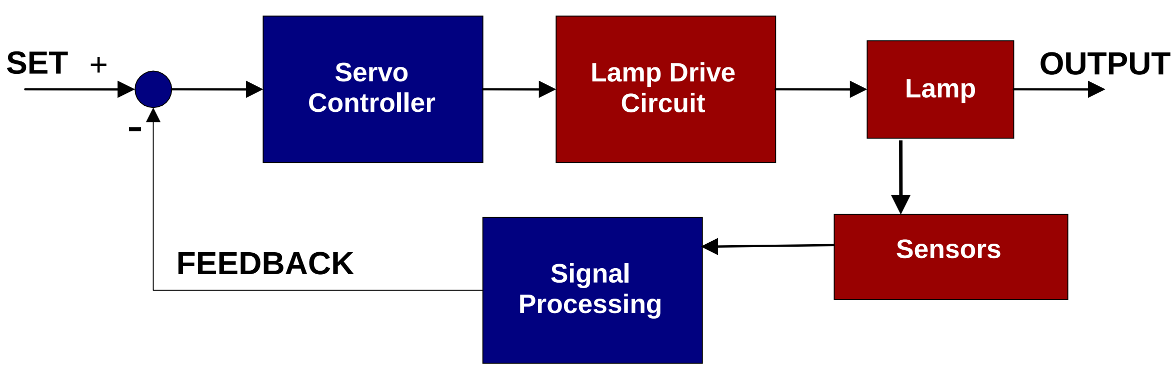

Figure 4: Servo Control System

Average Optical Power Control Servo (AOP)

Depending upon the desirable amount of margin bias current over the threshold, an additional amount of current (called noise threshold margin N_{TH}) may be applied as a result of the measured threshold. The System Configuration has a means to specify the incremental amount of bias current. Once the threshold current has been determined, the Bias Control Servo takes over the bias control. Bias is maintained with a high degree of precision over temperature and, data transmission no disrupted while this servo is in action.

Optical Modulation Amplitude and Extinction Ratio Control Servo (OMA and ER)

The modulation control servo ensures consistent modulation output as appropriate for the application. The modulation servo uses temperature and feedback information from the CEYX microdetector. The feedback information allows the Modulation Servo to maintain the value for the OMA and ER with data is transmitted. Furthermore, the modulation servo will provide a high level of precision over temperature. A unique feature of this servo is that it also provide aging compensation. Data transmission is not disrupted while this servo is in action.

Transceiver Nonlinear Models

Analog behavior of components used in the transceiver can significantly influence optical signal performance. For example, driver ICs can exhibit nonlinear characteristics or output current versus input voltage. Monitor Photodiodes (MPDs) used in the laser assembly can exhibit temperature drift. Laser, especially VCSEL lasers can exhibit significant nonlinearities. For critical applications, the CEYX solution includes nonlinear mathematical models for all of these components. The nonlinear models are calibrated at ambient temperature during production and provide the needed stability over temperature and part to part variation.

CEYX Microdetector

This unique feature of the CEYX solution will transform the way optical transceivers are managed. A minute amount of current is injected into the laser transmission path. The characteristic of the power spectrum and frequency of the injected current is such that it will not significantly add to the transmitted optical signal. The MPD output signal resulting from the injected current undergoes processing. Processing consists of amplification followed by a high-performance digital signal processor. Digital signal processing extracts a signature from the recovered MPD signal. The signature yields parameters which allow the determination of needed laser characteristics such as slope parameters which allow the determination of needed laser characteristics such as slope efficiency, threshold and degree of aging. All of this operation is conducted while data is transmitted. This approach allows closed loop servo control of modulation over temperature, aging compensation and the possibility to report to the network host any anomalies found as well as to warn of needed laser maintenance, repair or replacement.

Expert Threshold Detector

The Expert Threshold Detector is an Expert System with adaptive decision-making and is used to determine the threshold for any laser diode. The Expert System is a program that emulates decision made by a human operator when determining the threshold of a laser diode. The process consists of activating the threshold detector during power-up initialization, and then controlling the bias and modulation currents to obtain a set of data points of laser power (measured with a photodiode) versus laser current. The threshold is determined with embedded signal processing and decision criteria.

Laser Control Hardware

The Laser Control Hardware implementation is simplified by use of an off-the-shelf mixed signal microcontroller (MCU). Figure 6 shows an example of a possible implementation. The approach enables very rapid development because it emphasizes firmware functionality geared to provide flexibility and low cost. Any MCU platform can be supported along with multiple types of drivers and sensors.

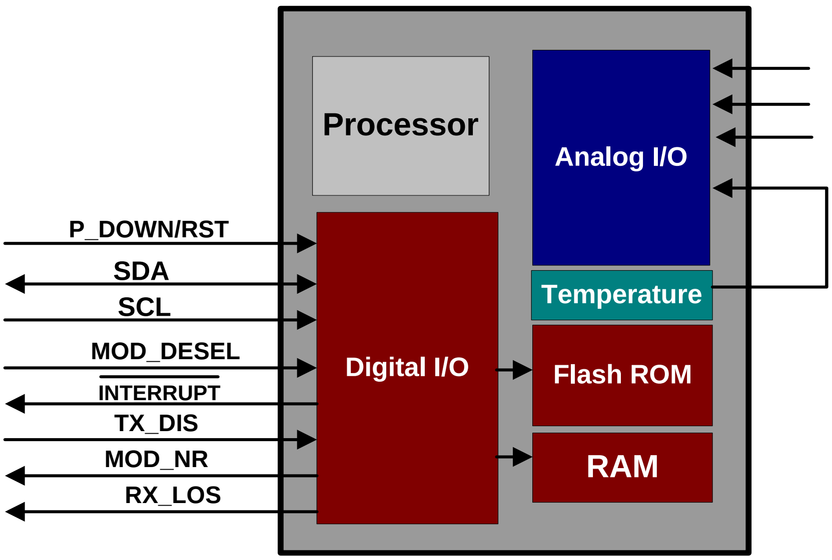

Figure 6 Laser Control Hardware

Conclusions

The CEYX Software Enabled Control System allows unprecedented levels of flexibility to address controls for multiple types of lasers. Old assumptions constraining embedded control are disappearing. The dynamic interaction of the control algorithm and the platform – hardware and software – requires a system level perspective not previously available. Through development of software architecture that allows heterogeneous components to interoperate across diverse platforms and network protocols, enables dynamic reconfiguration and evolution of systems while they are still running. Configuration is immediate and allows for a host computer to perform periodic maintenance and communication with the transceiver. Servo Controls provide high level of precision and application flexibility. The result is transceiver manufacturers now have a powerful new way to reduce the costs associated with new design delivery, and at the same time, reduce the risks associated with every changing network demands.

References

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Contacts: info@CEYX.com
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