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A 155 Mbps laser diode driver with automatic power and extinction ratio control*

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Abstract: An integrated laser diode driver (LDD) driving an edge-emitting laser diode was designed and fabricated by 0.35 μm BiCMOS technology. This paper proposes a scheme which combines the automatic power control loop and temperature compensation for modulation current in order to maintain constant extinction ratio and average optical power. To implement temperature compensation for modulation current, a novel circuit which generates a PTAT current by using the injecting base current of a bipolar transistor in saturation region, and alternates the amplifier feedback loop (closed or not) to control the state of the current path is presented. Simulation results showed that programmed by choice of external resistors, the IC can provide modulation current from 5 mA to 85 mA with temperature compensation adjustments and independent bias current from 4 mA to 100 mA. Optical test results showed that clear eye-diagrams can be obtained at 155 Mbps, with the output optical power being nearly constant, and the variation of extinction ratio being lower than 0.7 dB.

Key words: Laser diode driver (LDD), Automatic power control (APC), Extinction ratio, Temperature compensation
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INTRODUCTION

The increasing demand for high-speed transport of data has stimulated optical communications, leading to extensive design of high-speed integrated circuit. In optical communication systems, a laser diode driver (LDD) is the key component of optical transmitter. As the size and area of optical modules decrease, the operating temperature increases due to the close proximity of the modules in a complete system. Small form factor (SFF, SFP) modules, for example, allow for very high module densities on a line card. The elevated temperatures associated with high module density can have significant effect on the module's performance due to the temperature dependent variables of the laser. As the characteristics of edge-emitting laser diode change over time and temperature in that the threshold current increases with rising temperature while the current-to-light conversion efficiency or slope efficiency decreases with rising temperature (Razavi, 2003), extinction ratio and average power which derived from the slope efficiency and threshold current associated with the laser diode are the key parameters affecting the performance of an optical system. In optical module design, most fiber-optic transmitters are required to keep average power constant and minimize extinction ratio variation over a broad temperature range (e.g. −40~+85 °C).

How to compensate for these changes in order to maintain constant extinction ratio and average power is a hotspot issue, and some circuit design techniques have been proposed, e.g., digital automatic power control for controlling the average power and extinction ratio (Fu and Chen, 2006), a statistic parameter-

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ized control loop (Chen, 2005) and a scheme which combined the automatic power control loop and automatic modulation control loop (Martinez and Tan, 2004) for compensating power and extinction ratio of a laser diode. This paper proposes a scheme which combines the automatic power control loop and temperature compensation for modulation current in order to maintain constant extinction ratio and average optical power. The modulation current with temperature compensation adjustments is used to track the variation of the LD's slope efficiency. And the automatic power control loop can adjust the value of the bias current to track the LD's threshold current change over time and temperature.

ARCHITECTURE AND CIRCUIT DESIGN

The block diagram of the proposed LDD is presented in Fig.1. The driver accepts differential PECL inputs ($V_{IN}+/V_{IN}-$), drives the block Modulator to modulate I_{MOD}, and then drives the laser diode. When the input is high, that is to say, $V_{IN}+$ is at high voltage and $V_{IN}-$ at low voltage, its output drives laser diode with modulation and bias current (I_{MOD} and I_{BIAS}). The APC loop adjusts the value of the bias current. The TCC module provides temperature compensated modulation current.

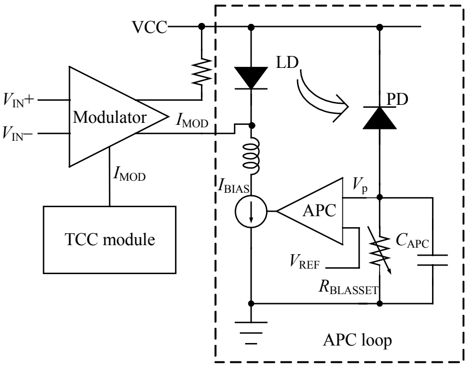


Fig.1 Block diagram of the proposed laser diode driver

Average power control

The average optical power can change dramatically over temperature due to changes in threshold current. As the threshold current increases, more laser current is required to maintain the same average power.

In order to compensate for changes in the laser threshold current over temperature, automatic power control (APC) loops can be used. The APC loop is shown in dotted block of Fig.1. It works as follows: A monitor photodiode (PD) mounted in the laser package transforms the laser optical power into a proportional photocurrent, then, the current is converted into voltage by a single external resistor $R_{BIASSET}$, the voltage at V_P will be low-pass filtered compared with a reference voltage V_{REF}. The resulting error then adjusts I_{BIAS} so that V_P approaches V_{REF} (Lin *et al.*, 2002; Zivojinovic *et al.*, 2004). Given that the relationship between the photodiode current and average power is ideally linear, the average power is held constant by keeping the photodiode current at a constant level. The optical output power level is set by the value of external resistor $R_{BIASSET}$.

Extinction ratio control

The slope efficiency of the laser can also change greatly over temperature. This change in slope efficiency can easily cause the extinction ratio to vary by 4 dB or more, from −40 °C to +85 °C, when the average power is held constant.

Some attempts to use temperature coefficient compensation for modulation current to compensate the variations in extinction ratio can be found, e.g. in (Shastri *et al.*, 1991; Seshimo, 2004). However, the temperature at which modulation current compensation starts ($T_{TCSTART}$) cannot be adjusted in (Shastri *et al.*, 1991), and circuit structure is complex in (Seshimo, 2004) and also in (Shastri *et al.*, 1991). This paper proposed a Temperature Compensate Circuit (TCC) to provide a programmed temperature compensated modulation current as shown in Fig.2.

The TCC module consists of the block TCSTART module, TCSLOPE module, MODSET module and SUM module. The current injected to the block Modulator for modulation (i.e. I_{MOD}) has two components: (1) $I_{PTAT1}=V_{PTAT1}/R_{MODSET}=k_1T/R_{MODSET}$, the current which slowly increases with rising temperature is supplied to the block Modulator over the entire temperature range. It is generated using V_{PTAT1}, which is generated by the block bandgap reference BGREF1 and its amplitude is set by an external resistor R_{MODSET} through the block BUF; (2) Beyond a given temperature ($T_{TCSTART}$), the modulation current increases more rapidly by adding an additional

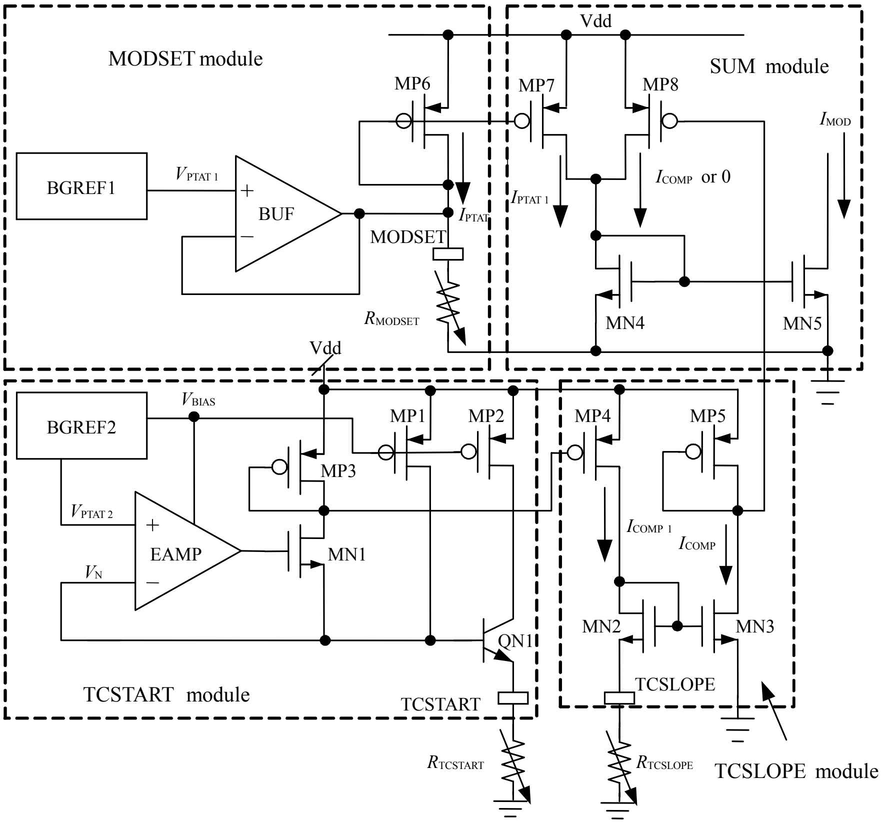


Fig.2 TCC simplified circuit schematic of the temperature compensated circuit

current component I_{COMP} with selectable slope. The additional current component I_{COMP} is provided to compensate for temperature induced changes in slope efficiency. T_{TCSTART} and I_{COMP} are all generated by the block TCSTART module and TCSLOPE module. A detailed analysis is given in the following paragraphs.

The signals generated by the bandgap reference module BGREF2 are V_{PTAT2} (about 1.25 V) and V_{BIAS}. V_{PTAT2} has a positive temperature coefficient k_{01} (i.e. $V_{\text{PTAT2}}=k_{01}T$) as shown in Fig.3, which is used as the reference voltage at the noninverting input of the error amplifier EAMP. V_{BIAS} is used for biasing the EAMP circuit and the transistors MP1 and MP2. The transistor QN1 is biased on the region of saturation by setting appropriate currents $I_{\text{D(MP1)}}$ and $I_{\text{D(MP2)}}$, where the currents $I_{\text{D(MP1)}}$ and $I_{\text{D(MP2)}}$ are biasing currents of the transistors MP1 and MP2 respectively, which have a slight positive temperature coefficient, i.e., $I_{\text{D(MP1)}}=k_{02}T$, $I_{\text{D(MP2)}}=k_{03}T$.

As $V_{\text{BE(QN1)}}$ (the base to emitter voltage of transistor QN1) has a negative temperature coefficient (i.e., $V_{\text{BE(QN1)}}\approx -k_{04}T$), the voltage V_{N} also has a negative temperature coefficient. Setting the value of V_{N} by selecting the value of R_{TCSTART}: $V_{\text{N}}>V_{\text{PTAT2}}$, up to a given temperature T_{TCSTART}. When $V_{\text{N}}>V_{\text{PTAT2}}$, the EAMP compels the voltage at the output, which is connected to the gate of transistor MN1, approaching ground voltage. So, in this case, the transistor MN1 is off, $I_{\text{D(MP3)}}=0$, $I_{\text{COMP}}=0$, no additional current injects to the SUM module. And then,

$$V_{\text{N}}=[I_{\text{D(MP1)}}+I_{\text{D(MP2)}}]R_{\text{TCSTART}}+V_{\text{BE(QN1)}}. \quad (1)$$

With rising ambient temperature, V_{N} approaches V_{PTAT2} at the temperature T_{TCSTART}, as shown in Fig.3. So the voltage at the output of the EAMP rises, the transistor MN1 turns on, which closes the feedback path. From this temperature, the value of V_{N} will follow that of V_{PTAT2} (also shown in Fig.3), that is to say,

$$V_{\text{N}}\approx V_{\text{PTAT2}} \;\; (T\geq T_{\text{TCSTART}}) \quad (2)$$

for $V_{\text{PTAT2}}=k_{01}T$, $V_{\text{BE(QN1)}}\approx -k_{04}T$. Combining Eqs.(1) and (2), we have

$$T_{\mathrm{TCSTART}}=[I_{\mathrm{D(MP1)}}+I_{\mathrm{D(MP2)}}]R_{\mathrm{TCSTART}}/(k_{01}+k_{04}). \quad (3)$$

From Eq.(3), we see that the value of T_{TCSTART} is varied with that of R_{TCSTART}. So T_{TCSTART} can be easily adjusted according to the characteristics of the laser used, this is also shown in Fig.3.

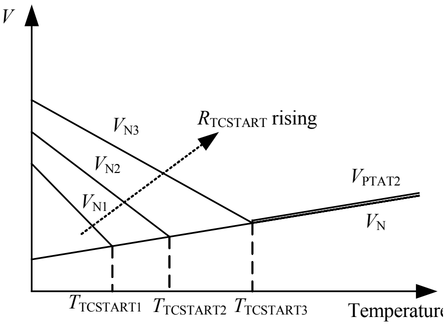


Fig.3 The sketch map of V_{N} vs V_{PTAT2} and T_{TCSTART} vs R_{TCSTART}

Beyond the temperature T_{TCSTART}, the transistor MN1 is on, the transistor MP3 can supply drain current $I_{\mathrm{D(MP3)}}$. The voltage V_{N} will be

$$V_{\mathrm{N}}=[I_{\mathrm{D(MP1)}}+I_{\mathrm{D(MP2)}}+I_{\mathrm{D(MP3)}}]R_{\mathrm{TCSTART}}+V_{\mathrm{BE(QN1)}}. \quad (4)$$

For $T>T_{\mathrm{TCSTART}}$, from Eq.(4) we see that to maintain the value of V_{N} following the value of V_{PTAT2}, the total currents through the resistor R_{TCSTART} have to be increased. The added current component is just $I_{\mathrm{D(MP3)}}$ which is drawn from MP3. Ignore the effect of the injecting base current variation on $V_{\mathrm{BE(QN1)}}$, then, for $T\geq T_{\mathrm{TCSTART}}$,

$$I_{\mathrm{D(MP3)}}=\frac{k_{01}T+k_{04}T}{R_{\mathrm{TCSTART}}}-I_{\mathrm{D(MP1)}}-I_{\mathrm{D(MP2)}}\approx k_{05}T. \quad (5)$$

In conclusion, for $T<T_{\mathrm{TCSTART}}$, the transistor MN1 is off, the EAMP is "open", $I_{\mathrm{D(MP3)}}=0$, that is to say, the current switches off; for $T\geq T_{\mathrm{TCSTART}}$, the transistor MN1 is on, the EAMP loop is "close", $I_{\mathrm{D(MP3)}}\approx k_{05}T$, that is to say, the current switches on, and $I_{\mathrm{D(MP3)}}$ has a positive temperature coefficient.

I_{COMP1} is the current $I_{\mathrm{D(MP3)}}$ mirrored with gain n_1, i.e., $I_{\mathrm{COMP1}}=n_1k_{05}T=k_{06}T$. The transistors MN2 and MN3 are two matched NFETs with size W/L. Assume the threshold voltages V_{th} of the transistors MN2 and MN3 are the same, then the drain current of the transistor MN3 ($I_{\mathrm{D(MN3)}}$) is deduced as

$$\begin{aligned}I_{\mathrm{D(MN3)}}&=I_{\mathrm{COMP1}}+\sqrt{2\mu_n c_{\mathrm{ox}}W/L}R_{\mathrm{TCSLOPE}}(I_{\mathrm{COMP1}})^{3/2}\\&+\frac{1}{2}\mu_n c_{\mathrm{ox}}W(R_{\mathrm{TCSLOPE}}I_{\mathrm{COMP1}})^2/L,\end{aligned} \quad (6)$$

where μ_n is the mobility of electrons, c_{ox} is the gate oxide capacitance per unit area, R_{TCSLOPE} is the value of an external resistor $\mathrm{R_{TCSLOPE}}$ which is connected as shown in Fig.2. For a given R_{TCSLOPE}, Eq.(6) can be represented as:

$$I_{\mathrm{D(MN3)}}\approx k_{06}T+k_{07}T^{3/2}+k_{08}T^2. \quad (7)$$

The current $I_{\mathrm{D(MN3)}}$ is mirrored with gain n_2 for generating the current I_{COMP},

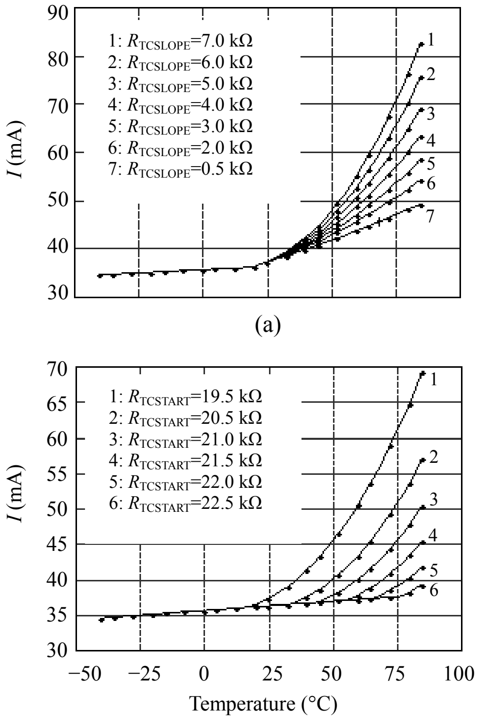
$$I_{\mathrm{COMP}}\approx n_2(k_{06}T+k_{07}T^{3/2}+k_{08}T^2)=k_2T+k_3T^{3/2}+k_4T^2. \quad (8)$$

From Eqs.(6) and (8), we can see that I_{COMP} is the current which increases more rapidly with rising temperature, and its temperature coefficient can be easily adjusted by the external resistor R_{TCSLOPE}.

To sum up, programmed by choice of external resistors R_{TCSTART} and R_{TCSLOPE}, I_{MOD} will have the desired value to track the changes in LD's slope efficiency over the operation temperature. Simulation results illustrated in Fig.4 shows that the range of modulation current temperature coefficient can be adjusted from 4×10^{-4}/°C to 2×10^{-2}/°C, and that the range of programmable temperature at which modulation current compensation starts can be adjusted from 20 °C to 75 °C. Simulations were performed by using the 0.35 μm BiCMOS lib, laser diode is replaced by an equivalent circuit (Chen *et al.*, 2001; 2002). All results shown are based on back-annotated simulations including all layout parameters.

EXPERIMENT RESULTS

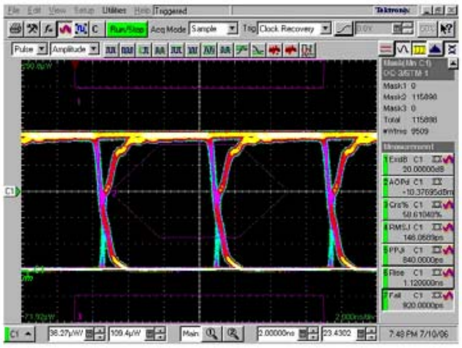
The driver circuits are designed to provide modulation current from 5 mA to 85 mA and bias current from 4 mA to 100 mA for driving an edge-emitting laser diode. The circuit has been fabricated in a 0.35 μm BiCMOS process. Optical test (test laser diode is a SONY DFB LD) shows that clear eye-diagrams can be obtained at 155 Mbps data rates and average light output power of the driver was measured to be ±0.1 dB maximum variations over the ambient temperature and operating voltage ranges, and that the variation in extinction ratio over temperature is lower than 0.7 dB. Fig.5 illustrates an eye-diagram of the optical output @155 Mbps at 27 °C, when driven with pseudo-random ($2^{13}-1$) input signal.



(a)

(b)

Fig.4 (a) R_{MODSET}=5 kΩ, R_{TCSTART}=20 kΩ, I_{MOD} vs R_{TCSLOPE} over −40~85 °C; (b) R_{MODSET}=5 kΩ, R_{TCSLOPE}=5 kΩ, I_{MOD} vs R_{TCSTART} over −40~85 °C



Mask1 0
Mask2 115890
Mask3 0
Total 115890
#Wfms 9509

1 ExtdB C1 20.00000dB
2 AOPd C1 −10.37695dBm
3 Crs% C1 50.61040%
4 RMSJ C1 146.0569ps
5 PPJ C1 840.0000ps
6 Rise C1 1.120000ns
7 Fall C1 900.0000ps

Fig.5 Optical output eye-diagram @155 Mbps at 27 °C

CONCLUSION

A driver for driving an edge-emitting laser diode with independently adjustable bias and modulation currents has been discussed. The laser driver features automatic power and extinction ratio control. In order to provide temperature compensated current to track the changes of the LD's slope efficiency over temperature in order to minimize the variation in extinction ratio, a novel circuit is proposed and thoroughly analyzed in this paper. Experimental results showed that the proposed automatic power and extinction ratio control approaches work very well.

References

Chen, W.Y., Yang, S.R., Liu, S.R., 2001. Optoelectronic Devices Circuit Model and the Circuit-Level Simulation of OEIC. National Defense Industry Press, Beijing, p.97-123, p.224-243 (in Chinese).

Chen, G.C., Chen, W.Z., Luo, R.H., 2002. A 2.5 Gbps CMOS Laser Diode Driver with Preamphasis Technique. 2002 IEEE AP-ASIC, p.97-123.

Chen, Y.L., 2005. Statistic Parameterized Control Loop for Compensating Power and Extinction Ratio of a Laser Diode. US Patent, No. 6909731, p.1-17.

Fu, S.M., Chen, C.Y., 2006. DC-coupled burst-mode laser diode driver with automatic power control for 1.25Gbit/s PON System. *Analog Integrated Circuits and Signal Processing*, **46**(2):159-164. [doi:10.1007/s10470-005-0907-8]

Lin, C.H., Yao, I.C., Kuo, C.C., Jou, S.J., 2002. 2.5Gbps CMOS Laser Diode Driver with APC and Digitally Controlled Current Modulation. Proc. 2002 IEEE Asia-Pacific Conference, p.77-80.

Martinez, C.G., Tan, Q.H., 2004. Controlling the Extinction Ratio of Optical Transmitters. US Patent, No. 6807209, p.1-9.

Razavi, B., 2003. Design of Integrated Circuits for Optical Communication Systems. McGraw-Hill, New York, USA, p.40-45.

Seshimo, T., 2004. Circuit for Generating Bias Current, Circuit for Driving Laser Diode, and Transmitter for Optical Communication. China Patent Application No. 200410038464.8, p.1-22 (in Chinese).

Shastri, K.R., Royer, J.J., Yanushefski, K.A., Benjamin, R.F., 1991. 1.2Gb/s Integrated Laser Driver with Temperature Compensation for Modulation Current. Proc. IEEE Custom Integrated Circuits Conference, p.2751-2754.

Zivojinovic, P., Lescure, M., Tap-Béteille, H., 2004. Design and stability analysis of a CMOS feedback laser driver. *IEEE Trans. on Instrum. & Meas.*, **53**(1):102-108. [doi:10.1109/TIM.2003.821487]