# Laser Drivers

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## 1.0 Introduction

The transmission capacity of communication systems has evolved tremendously over the past 150 years, bringing borders, people and places closer together. Arguably the first step in this journey was the made by Samuel Morse, when he transmitted the first electrical telegraph message in 1844. Following in his footsteps, a Scotsman by the name of Alexander Graham Bell furthered the drive for innovation into the Electric era, by realizing the transmission of spoken words by electric currents through a telegraph wire; his invention was the telephone in 1876. Trends in analog and eventually digital communications continued profusely through the electronic and into the microelectronic era with the inauguration and expansion of wireless and satellite links. Again and again scientist and engineers managed to exploit bandwidths and push the limits of information travel until constraints of practicality due to noise, interference, power, cost and other issues began limiting progress. An analogous progression to the evolution of communication, would be one of personal travel, whereby, although man has reached the practical limits of water (telegraph), land (telephone) and atmospheric/aircraft (wireless) based travel, the speed and achievement of space travel are not limited by any inherent boundaries of space, rather only by our inabilities to supply the adequate technological means. The equivalent bottlenecks in the exploitation of fibre's seamlessly unlimited bandwidth lay at and in between the electrical-optical/optical-electrical transducer interfaces of today's fastest optical links; a key part of which is the laser or modulator driver.

Therefore, to understand the role and imposing design constraints of this critical optoelectronic component, a general understanding of the system into which it integrates must be established.

## 2.0 Optical Transceivers

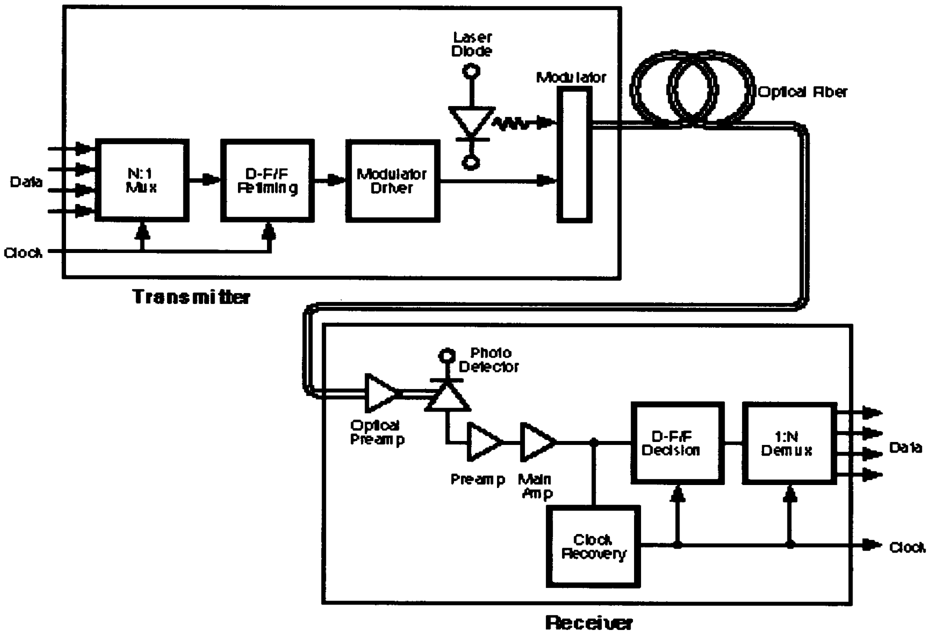

**FIGURE 1. Transmit, Channel and Receive Sections of an Optical Telecommunications Link [1]**

### 2.0.1 High-Speed Transmitter

The optical transceiver begins with a high speed multiplexer, used to concentrate a number of lower speed signals into one high speed bit stream. For instance, an OC-192 (10Gb/s) channel would be implemented by multiplexing 4 existing OC-48 (2.5Gb/s) channels together into a 10Gb/s data stream. The multiplexed data is then often retimed to remove any phase jitter before being applied to a laser (or modulator) driver to boost the voltage and current to the level required by the opto-electronic device. This electrical to optical transduction can be implemented classically using direct modulation of a light emmitting diode (LED) or laser diode (LD), typically for shorter distances and lower speeds, or by external modulation of a more advance Distributed Feeback Laser (DFB) or an optical modulator (consisting of either an Electro-absorption (EA) modulator or Mach-Zehnder Interferometric (MZ) modulator and a laser), generally called upon to meet higher speed and distance requirements. Because figure 1 is a portrayal of a more sophisticated optical transceiver for common 10Gb/s links or faster, an optical modulator (comprised in this case of the laser and EA/MZ modulator block) and a modulator driver are utilized on the transmit side. Equivalent speeds would also be attainable using an advanced laser, such as a Distributed Feeback Laser (DFB), modulated by a laser driver. In either case, the circuit design considerations, other than the impedance matching at the output of the driver, are all identical and thus the terms are used interchangeably. All of the aforementioned components are solid state devices, which by virtue of their small size, high reliability and stability, modest power supply requirements, long life time, ease of modulation and low cost, are the preferred light sources for fiber optical communication systems. However, because of the material incompatibilities the laser, modulator driver and modulator must be fabricated on separate substrates and must be interconnected by transmission lines. In essence, the described transducer produces an optical signal output that is modulated in direct accordance to the high speed data bit stream, and is ready for transmission through the optical fibre.

### 2.0.2 Fibre Optic Channel

Along the fibre optic channel, the modulated pulses suffer form attenuation, in its classical sense, and dispersion, which is defined as the pulse spread due to the varying refraction of light of different wavelengths along the channel and is measured in picoseconds per kilometer per nanometer [ps/(km nm)]. Compensation for the linear dispersive effects introduced by the fibre will be addressed shortly.

### 2.0.3 High-Speed Receiver

When the modulated light signal reaches the receiver side, as illustrated in figure 1, it is optically amplified using an Erbium Doped Fiber Amplifier (EDFA) before being applied to the photodetector. This is an optional step which has been included to demonstrate the repeating capability of optical fibres using EDFAs for long-haul applications (>300km). The photodectector is a solid state receiver/detector, such as a P-I-N diode (whose acronym corresponds to the physical layers of it’s structure), which essentially acts as a photon-electron converter and is utilized for the same benefits that accompany solid state light sources. The output current generated by the photodetector is generally weak, and therefore requires transimpedance amplification in order to obtain a sufficient voltage level that can be used to correctly decide wether each transmitted bit is a ‘1’ or a ‘0’. In accordance to figure 1, the first stage in this amplification is accomplished by a transimpedance amplifier (or pre-amp) whose design goals usually strive for high bandwidth, low noise, large dynamic range (difference between min and max input voltage levels whose output values will still meet specifications, for instance a minimum BER) and obviously high transimpedance. A filter is often used to suppress noise and reduce Inter-Symbol Interference (ISI) either between the pre and post amplifier or after the Automatic Gain Controller (AGC) amplifier (main amp). The linear dispersive effects introduced along the fibre optic channel can also be removed by means of equalization in the receiver, often incorporated into the aforementioned filtering process. The second stage in the amplification process is accomplished by the AGC, which ensures that the output bit stream is one of constant amplitude before being inputted into the clock recovery and decision circuit. The clock recovery circuit extracts the clock signal and applies it to the decision circuit as shown in order to make an optimal decision as to the correct binary value of each bit of the input stream in the face of the degradation the signal has endured. The recovered signal is then demultiplexed to lower speeds for further decoding and processing by conventional electronics.

## 3.0 Methods of Emission for Optical Transmission

With a firm understanding of the overall optical transceiver system, it is now possible to focus on one of its crucial optoelectronic components, the laser driver. In general, there are two methods and four types of devices available for the transmission of data over optical fiber: direct modulation with LEDs or LDs and indirect/external modulation with either EA or MZ modulators. The operation and characteristics of these light sources must be discussed and analyzed before delving into the task of designing circuitry to modulate them.

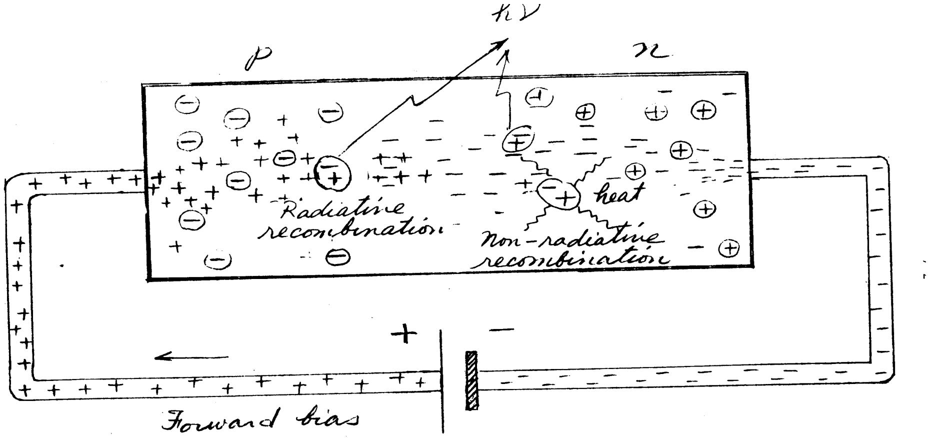

**FIGURE 2. (a) Distribution of Charge Carriers in an LED - note the forward bias to permit injection of electrons and holes**

## 3.1 Light Emitting Diode (LED)

LEDs generate modulated light by means of spontaneous emission, meaning that the emitted light is uninfluenced by external illumination and generated solely due to the current applied to the junction. Figure 2(a) illustrates the charge distribution in a simple LED. When electrons and holes are injected into the junction region, electrons with high energy ($E_2$) settle down into positions of missing valance electrons (lower energy level $E_1$), releasing light energy $E_g$ = hv, where v is the frequency of the emitted light and h is the Planck's constant. For an LED, the highest modulation frequency possible is determined by the recombination time; or simply the time injected electrons take to recombine. Furthermore, it is clear that not all of the recombinations that will take place will release the same energy due to non-uniformity of the energy of the injected electrons. For this reason, spontaneous emission of an LED (and in general) possesses none of the characteristic properties of laser light since the radiation is emitted through a wide angular region in space (making efficient coupling into an optical fiber rather difficult), the light is phase incoherent and the emission is often polychromatic, meaning the emitted light can have a frequency spectrum with a large spread (resulting in half power widths as wide as a hundred Angstroms). As a result, LEDs are only useful for short to moderate transmission distances because wider spread in frequency means wider dispersion in the optical fiber.

Nevertheless, the first optical transmission experiments were performed with LEDs and therefore, a brief discussion of these primitive drive circuits will help put newer designs into perspective.

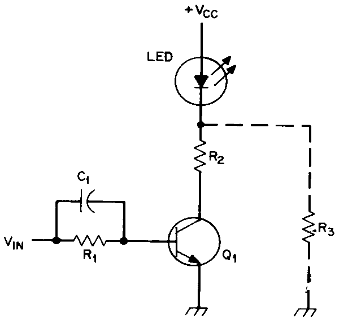

FIGURE 2: (b) A common-emitter saturating switch

Back in the 1980’s, 50-300mA switching current was needed to modulate an LED at high speeds in accordance with low-level data input. The circuit of figure 2(b) is one of the simplest possible driving circuits, using a common emitter configuration to switch current through the LED along with a shunt resistor, $R_3$, to maintain a constant bias current through the LED. The circuit offers current gain across the transistor, a small voltage drop across the switch (Vce(sat)~0.3V) and ease of providing independent bias to the LED through $R_3$. For certain LED’s, the speed can be limited by the fact that the LED drive appears to come from a current source (the reverse-biased collector base junction). Thus, if the LED has a high capacitance, drive current is initially diverted into charging this capacitance, reducing the current available for light generation. This can be somewhat offset by using the speed-up capacitor at the base, as illustrated in figure 2(b).

A more complex and complete ECL-compatible emitter-coupled LED driver is illustrated in appendix A. Older driver designs, including laser driver designs, were implemented using Emitter-Coupled-Logic (ECL). ECL uses emitter follower outputs to drive signals. ECL drivers were the circuits of choice due to the small output impedance of the emitter follower which supports a large fanout and makes it possible to drive large capacitive loads with small delay. However, the problem with ECL is that it occupies a much larger area than conventional bipolar design and consumes a lot more power.

## 3.2 Lasers

Solid state lasers use stimulated emission to generate light by creating a large population of high energy electrons ($E_2$) and a small population of lower energy electrons ($E_1$) within a cavity surrounded by two highly reflective surfaces (ie. polishing the ends of a laser diode). Due to the unbalance, an initial electron will eventually revert to the lower energy state, releasing a photon with energy $E_{21}=hv_{21}$; however this time varies depending on the elemental composition of the semiconductor laser (this fact will be important in understanding direct and external modulation in the next section). This photon might stimulate a second electron to descend in step to $E_1$ thus causing the emission of another photon which vibrates in phase with the first one. The two photons are consequently phase coherent and will continue to travel within the cavity by means of reflection, simulating more and more electrons to descend in step to $E_1$, creating a chain reaction, and eventually an avalanche of photons. In short, stimulated emission of light occurs when electrons are forced by incident radiation to add more photons to an incident beam. As a result, laser light is highly monochromatic because it is generated by electron transitions between two narrow energy levels (or simply the specific energy step is induced, rather than being decided by the random energy of the injected electrons; as was the case with the LED). The wavelength of the emitted laser light depends on the elements used in creating the semiconductor device, attributed to the various band gap energies. For a more in depth treatment of lasers in general refer to [6], [7], [8] and [9].

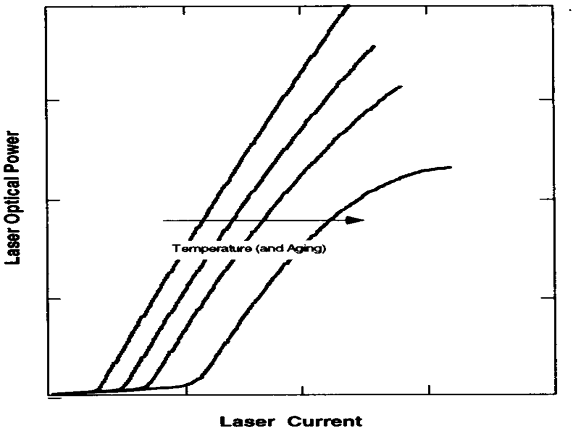

**FIGURE 3. A typical light vs. current curve for a laser diode illustrating qualitatively the effects of increasing temperature and aging [1].**

From this brief analysis, it is clear that the intensity of the emitted laser light is dependent on the concentration of charge carriers ready to induce avalanche photon production (in this case electrons). Because the charge carriers are supplied to the semiconductor laser by application of current, this minimum concentration corresponds directly to the threshold current of the laser, below which no light emissions are generated. Above the laser current threshold, the light output from a semiconductor laser is roughly proportional to the current through it. As a result, the simplest way to modulate either the intensity (for TDM) or frequency (for WDM/DWDM) of the laser output is to modulate this driving current. Nevertheless, in designing drive circuitry, consideration must be taken for the sensitivity of lasing devices. Although the light output is roughly proportional to the current through the laser above threshold, as illustrated in figure 3, this relationship varies greatly with temperature and aging of the laser. Clearly, temperature fluctuations will greatly affect the stringent energy step requirements of stimulated electrons for perfect monochromatic emission. These drastic variations will be compensated for during design.

In addition, it is important to note that when the laser is operated very close to threshold, the output signal becomes chirped. Chirp is a phenomena wherein the carrier frequency of the transmitted pulse varies with time, and it causes a broadening of the transmitted spectrum. This can be intuitively understood by realizing that it is not very likely that a limited number of stimulated electrons present when the laser is operated around threshold, will all descend in step to $E_2$ to produce photons travelling at the exact same frequency (wavelength mismatches will be inevitably high, thus generating a highly chirped signal). Clearly, the chances of perfect photon coherence are much greater when the number of stimulated electrons and stimulating photons is exponentially higher, as is the case when the laser is operated well above the threshold level.

### 3.2.1 Direct and External Modulation of Lasers

The process of imposing data on the fiber optic channel is called modulation. The simplest and most widely used modulation scheme is called on-off keying (OOK), where the light stream is turned on or off, depending on whether the data bit is a 1 or 0. OOK modulated signals are realized in one of two ways: either by direct modulation of a semiconductor laser or an LED, or by using an external modulator. In both cases, the drive current into the semiconductor laser is set well above the threshold for a 1 bit and below (or at) threshold for a 0 bit. The ratio of the output powers for the 1 and 0 bits is called the extinction ratio. Ideally, a high extinction ratio is desired in order to be able to easily interpret the difference between transmitted 1's and 0's. Direct modulation is simple and inexpensive since no other components are required for modulation other than the light source (laser/LED) itself. However, the disadvantage of direct modulation is that the resulting pulses are considerably chirped (as described in the previous section), and are therefore limited by sharply worse dispersion limits when compared to unchirped pulses - as mentioned wider frequency spectrum means wider dispersion. To minimize chirp, the transmitted power of a 0 bit can be increased, therefore keeping the laser always well above threshold; the disadvantage of which is that the extinction ratio is reduced, degrading system performance. This is an important design trade-off that incorporates itself into the design of laser drivers.

Furthermore, the rapidity with which the device can be modulated is also affected by the level of current in the laser during the "off" state; also known as laser bias current (usually below laser threshold). If the laser is turned from completely "off" to "on", it will exhibit a random delay known as "turn-on delay'. This is illustrated in figure 4. For an applied current pulse of amplitude $I_p$ the turn-on delay is given by the derived expression:

$$\tau d = \tau th \times \ln\left(\frac{Ip}{Ip - Ith}\right)$$

However, if a bias current is present upon arrival of the pulse, the delay time is reduced to:

$$\tau d = \tau th \times \ln\left(\frac{Ip}{Ip + Ib - Ith}\right)$$

where tth (tau-th) is the delay at threshold (usually 2ns) and Ith is the threshold current. Therefore, turn-on delay can be reduced by using a low-threshold laser, using large modulated pulse amplitudes, or maximizing the biasing current of the laser. Note that maximizing the bias current will inadvertently decrease the extinction ratio of the modulated signal.

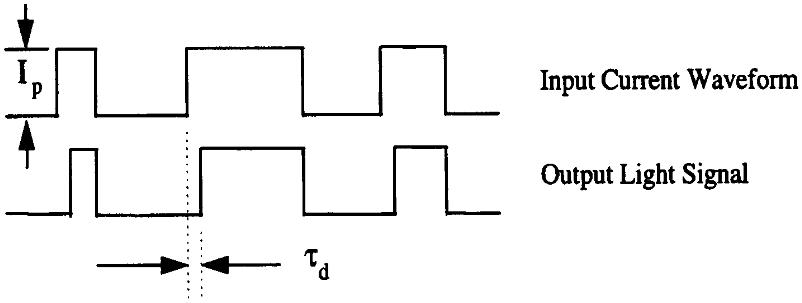

**FIGURE 4. Idealized laser input and output waveforms illustrating effects of laser turn-on delay**

Although in general, the operation of semiconductor lasers are all the same, as mentioned in the previous section, the time elapsed before electron avalanche begins varies depending on the composition. For instance, Erbium atoms have an extensively long lifetime at the $E_2$ level. This translates into extremely long switching times if the laser were to be directly modulated, hence drastically limiting the speed of transmission. This is the case for many lasers that are continuous wave sources, and therefore these lasers require an external modulator to achieve high modulation rates. The external modulator can be either an Electro-absorption (EA) modulator or Mach-Zehnder (MZ) interferometric modulator. EA modulators are attractive at high modulation rates because the wavelength chirp is much reduced relative to lasers and the drive voltage requirements are typically lower than that required for MZ types. This latter consideration is important given the common trade-off between the maximum voltage swing and the speed encountered in the available transistor technologies. However, MZ modulators can be driven to produce no chirp. Both modulator types are controlled by the applied voltage and present a predominantly capacitive load to the driver circuit (connected via a transmission line). A low output impedance driver is thus desired to insure that the low-pass characteristic of the resulting pole does not unduly limit the bandwidth. As will be seen, identical requirements are used in the design of a direct laser driver.

# 4.0 Design of Drive Circuitry

Although their design is simple in concept, there are stringent requirements that make the implementation of laser drivers very challenging, such as large output current requirements and ‘clean’ operation at full bit-rate. These requirements, as summarized in table 1, are imposed upon designers based on the limitations and variations of the modulated lasing device. Bipolar transistors are best suited for the design of laser drivers due to their very high current densities, high gain and high bandwidth.

**TABLE 1. Design Considerations and Possible Solutions in the Design of Laser Drivers**

| Design Constraint | Trade-offs | Possible Solutions |
|---|---|---|
| Output Power | • increases with extinction ratio (signal amplitude) | • monitor output power<br>• feedback and adjust bias |
| Dispersion | • between dispersion and laser chirp thus affecting whether direct or external modulation is used | • use of modulators can reduce or eliminate laser chirp<br>• Equalization can eliminate linear dispersive effects |
| Chirp | • large with direct modulation<br>• induces ISI, tradeoff with dispersion | • can use external modulators |
| Extinction ratio | • decreases with increased bias<br>• affects average output POWER | • balance according to requirements |
| Output Impedance matching (with transmission line connected to laser or modulator) | • high output impedance can limit bandwidth if laser has high input capacitance (modulators do)<br>• reflections caused by mismatch can affect extinction ratio and jitter | • low output impedance driver<br>• actively matched output |
| Bias current level | • affects speed and extinction ratio relationship and can control power | • low threshold laser<br>• used as control parameter |
| Temperature | • L-I characteristics of laser vary with temperature (figure 4) | • feedback control of bias current |
| Aging | • lasing threshold increasing with age because of an increase in inertial loss | • feedback control of bias current |

Although considerations for both direct and external modulator drivers were considered throughout this report as well as in the summary of table 1, the remaining analysis will concern itself with the design of direct modulator drivers only. Hence, the focus will be on traditional laser drivers. As mentioned, the circuit variations for a modulator driver are minimal, involving the consideration of an output stage for accurate transmission line matching (as part of the connection to the modulator).

## 4.1 Generic Feedback Compensation

Typically, the design of laser driver circuits incorporates the use of various feedback loops to compensate for variations in the mark density, temperature and aging. The mark density refers to the variation of the number of 1's and 0's in the data stream and is directly correlated to the output power of the laser. A simple approach at controlling the average output power of a laser is shown in figure 5.

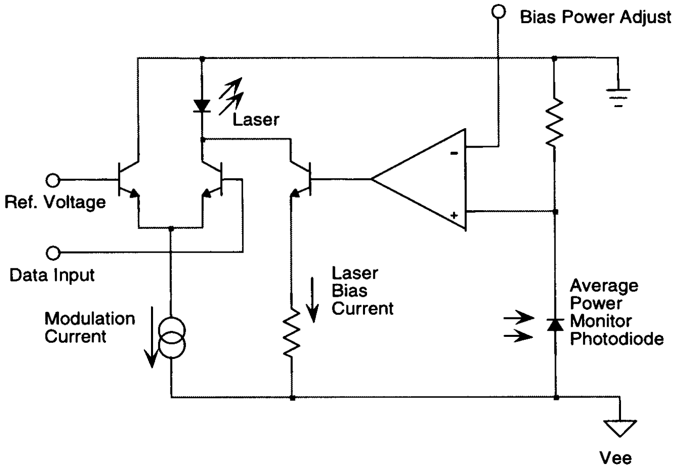

**FIGURE 5. Laser driver output stage with feedback control of the average output power**

Here the laser is directly connected to the collector of one transistor of a differential pair. As a result, the laser is modulated in accordance to the incoming bit stream when a constant reference voltage is applied to the other end of the diff pair, and the data values are applied to the gate of the drive transistor. As mentioned, to reduce the turn-on delay of the laser, a bias current is applied to the laser through the transistor in parallel with the drive transistor. This bias value is usually around threshold, as aforementioned, and the modulation current or added current above threshold for generating the stimulated emission of an optical 1 bit is determined by the constant current source biasing the differential pair in figure 5 (labelled as modulation current). The bias current is adjusted by a feedback loop in order to control the output power of the laser. The average power is monitored by means of a photodiode, converting approximately 8% of the output signal at the back facet of the laser, back to current for comparison at the op amp. Another approach is to utilize an optical tap and a photodiode connected to a portion of the transmitting fiber. The bias is then adjusted according to the difference between the feedback current across the resistor and the bias power adjust signal (which is derived directly from the desired output power of the laser). For instance, if the input signal from the photodiode is smaller than that from the bias power adjust, the bias current is increased to raise the output power level by increasing the Vbe of the bias transistor (and vice versa). This simple deign will maintain the output power levels of the 1's and 0's constant as long as the slope of the L-I curve and the relative density of 1's and 0's remain sufficiently constant. Automatic power control is also possible, however the circuit architecture is much more complicated as presented for the first time in [5].

Notice that although it was not mentioned directly, the change in temperature and increase in threshold potential due to aging are compensated for in the circuit diagram of figure 5. As illustrated in figure 4, although the L-I curve varies drastically with temperature and age, the relationship is still linear. As long as this is the case, regardless of whether the threshold potential of the laser is affected by changes in temperature or aging, the bias correction compensates for this because it considers only output power and varies the bias until this power requirement is met (thus the variation will be greater if substantial changes are induced by temperature or aging).

## 4.2 Mark Density Compensation

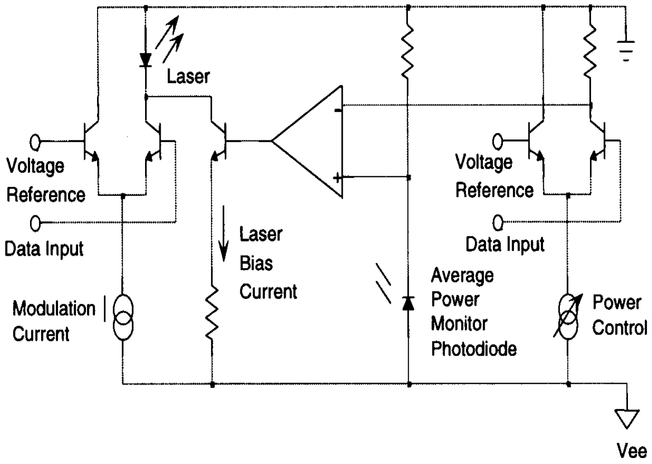

**FIGURE 6. Laser driver compensated for constant average power output and data mark density**

The average laser power is linearly related to the mark density because the transmission of a 1 bit requires so much more power than that of a 0 bit. A laser driver design that compensates for the fluctuations in the mark density is presented in figure 6. The data is applied to the driver circuit, as before, as well as to a circuit whose output is proportional to the mark density. This output is then used a reference to the bias control of the previous circuit. Now the amount of bias applied to the laser is less if there are more 1's in the input data stream and greater if there are more 0's. Again, the resistor in the added differential pair is calculated from the desired output power.

## 4.3 Laser Driver for High Modulation Rates

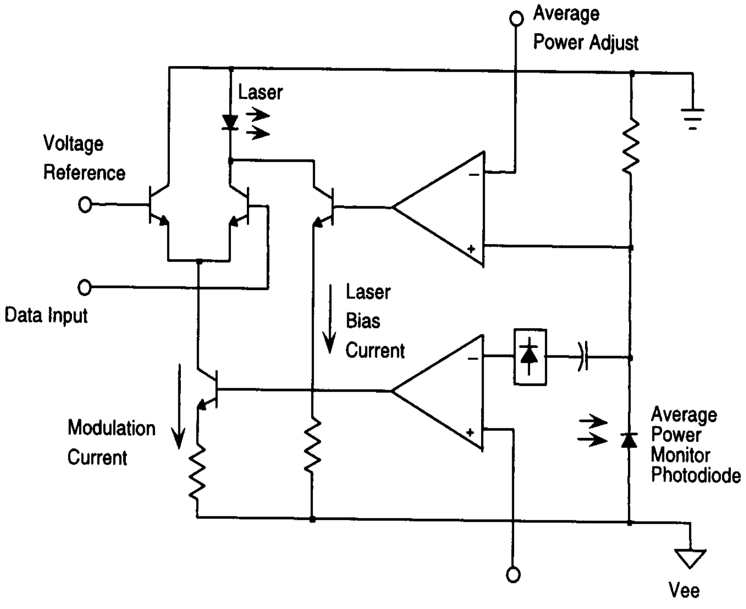

**FIGURE 7. Laser Driver with Feedback for Maintaining Constant Peak and Average Power**

A final generic approach is presented in figure 7 for high modulation rates. At speeds exceeding 10Gb/s, it is often desirable to have a significant bias applied to the laser in the 0 state to increase the speed of the laser and reduce the amount of ringing due to laser self-resonance. Clearly the problem arises as to the decrease in extinction ratio, whereby the level-difference between an optical 0 and optical 1 bit is reduced. Nevertheless, it results that the penalty in extinction ratio is more than compensated by the reduction in chirp as well as dispersion effects during transmission. However, to ensure consistency in the power levels of 1's and 0's (because now that the separation of the levels is greatly reduced, non-linear effects in the L-I characteristic which were not previously a problem might now become significant), the average power is now used to control the laser bias, and the peak power is used to adjust the peak modulation current as shown in the figure. The introduction of the capacitor allows for peak detection. The drawback, however, is that now each high speed pulse must be sensed, therefore requiring a high-speed photodiode controlling the feedback loop. Also, this design can be equipped with mark density compensation as per figure 6, in place of the average power adjust signal.

### 4.4 LED Drivers vs. Laser Drivers

In section 3.1, LEDs were introduced and a simple driving circuit was presented along with the complete ECL driving circuit in Appendix A. In addition to the high dispersion of LED emission, LED feedback control is very difficult to implement at high data-rates. The reason for this is that at higher bit rates (>1Mb/s with old LEDs), where most interest lies, the phase shifts and available gain in the LED output become a problem, hence making precise detection for feedback control near impossible. This is another reason why laser drivers, which as discussed can be designed to compensate for many variants of the lasing device, are the preferred method of transmitting high speed optically modulated signals.

## 5.0 Conclusions With Perspective

With a firm understanding of optical transmitters as well as the architecture and full functionality of laser driver circuitry, an insight would like to given towards the future of laser drivers. To add further perspective to the topic, we present two scenarios, the past and the present.

### 5.1 ECL Feedback-Stabilized Laser Driver (1978)

Figure 8 presents an old ECL laser driver design with laser output feedback from the mirror (back plate of the laser).

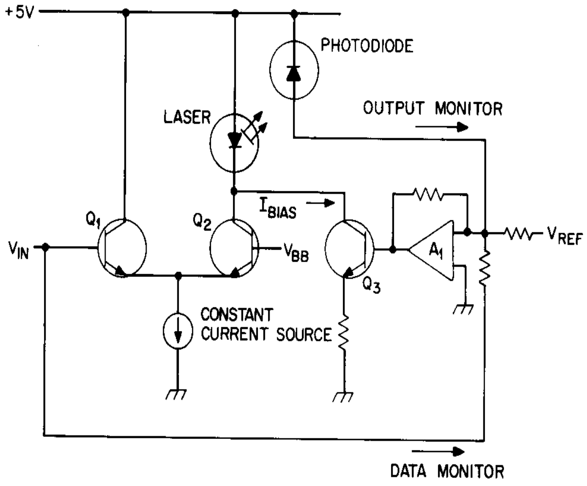

**FIGURE 8. ECL Laser Driver for Comparison with Proposed and Used Architectures**

## 5.2 The First 10Gb/s Laser Driver Design (1991)

Reference [10] presents the first laser driver design capable of integration into a 10Gb/s optical transceiver. The device was fabricated using InP/InGaAs heterojunction bipolar transistor technology based on material grown using hydride source molecular beam epitaxy (HSMBE). Figures 8 and 9 present the block diagram and circuit level schematic of the design.

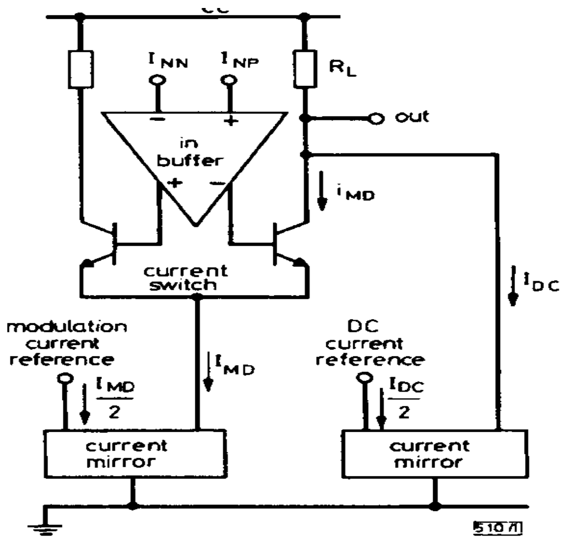

**FIGURE 9. Block Diagram of First 10Gb/s Laser Driver**

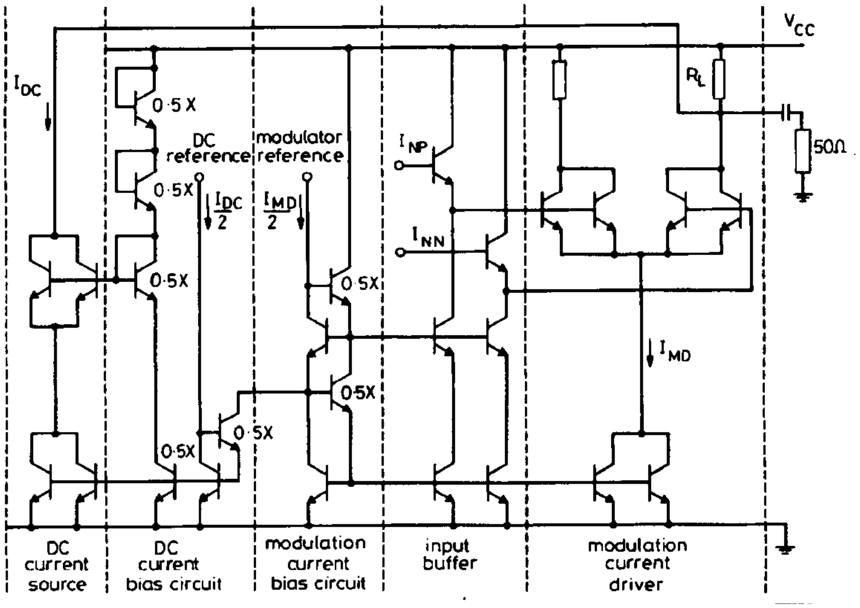

**FIGURE 10. Circuit Schematic of First 10Gb/s Laser Driver**

## 5.3 Comparative Analysis

In order to understand the direction of future laser driver designs and capabilities, it is important to review the breakthrough designs in the field of optical telecommunications. Sections 5.2 and 5.3 presented two laser driver design that were conceived over 10 years apart. However, the inherent architectures discussed in this report, involving a differential pair with resistive loading still remains pronounced in each design. Clearly the ECL design is higher level and involves feedback, but the new laser driver design focuses much more on the interfaces of the circuit with the laser and the prior optoelectronic component in the transmitter. The new design focuses much more on input and output buffering in order to minimize impedance values and not unduly reduce the bandwidth of the modulated signal. Furthermore, an enormous leap in transistor technology is also noted, bipolar ECL compared to InP/InGaAs high speed devices. Naturally, faster circuits can be designed and implemented with faster transistors.

As a result, a justifiable conclusion to make with regards to the future of laser drivers is that although the essential differential pair and resistive load will remain at the heart of the design, the peripherals will expand along with the speed. These peripherals include not only buffering, but automatic power control, actively matched output buffering and interconnect issues with the laser and other optoelectronic components (as presented in the references included in Appendix B). Although fancy, expensive and very fast transistor technologies can demonstrate incredible speeds in the laboratory, full implementation and industrial deployment requires reliable and cost effective solutions. These solutions come from integration as well as cheaper and more reliable transistor technologies. Therefore, laser drivers will improve with transistor technology, however cheap reliable solutions to standard network rates above OC-768 (40Gb/s) will remain as a bottleneck for future implementation.

# 6.0 References

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