Honeywell

Modulating VCSELs

Application Sheet

Introduction

One of the foremost applications of VCSELs is to transmit optical signals. These signals require modulation of the VCSEL to vary its emitted power. This application sheet provides information about VCSEL modulation that may assist in the design of optical transmitters. While many of the same principles apply to analog modulation applications, this sheet is aimed primarily at digital applications where data is encoded as ones and zeros, corresponding to pulses of high or low power, respectively.

The VCSEL behavior defined here is based on testing and analysis, but it must be considered typical, not assured. Some data is shown here for instruction and may not be representative of VCSELs available for sale; refer to data sheets for actual limits. Finally, while described behaviors may fit many VCSELs, they are specifically applicable to ~850-nm, proton-implanted devices intended for data communications. These devices can be identified by the Honeywell part number prefix *HFE*, as in *HFE4080-321*. (High-speed LEDs also use the *HFE* prefix.)

In this application note, symbols and names of characteristics are used interchangeably; many are defined in Table 1.

Some indication of responsible physical mechanisms is given, but the primary focus is description of the behavior itself. Models ignoring some details are presented both because they simplify calculations and because more complete models often require data that will be unavailable for individual devices. In some cases, two types of graphs are used in the explanations. The first demonstrates the general shape of the behavior for any VCSEL; the second includes sample behaviors of specific devices, giving some idea of possible device-to-device variations (again, however, note that some devices shown are intentionally outside production limits and are included for illustrative purposes only; sample data does not always represent actual production VCSELs). As an example, see Figure 1.

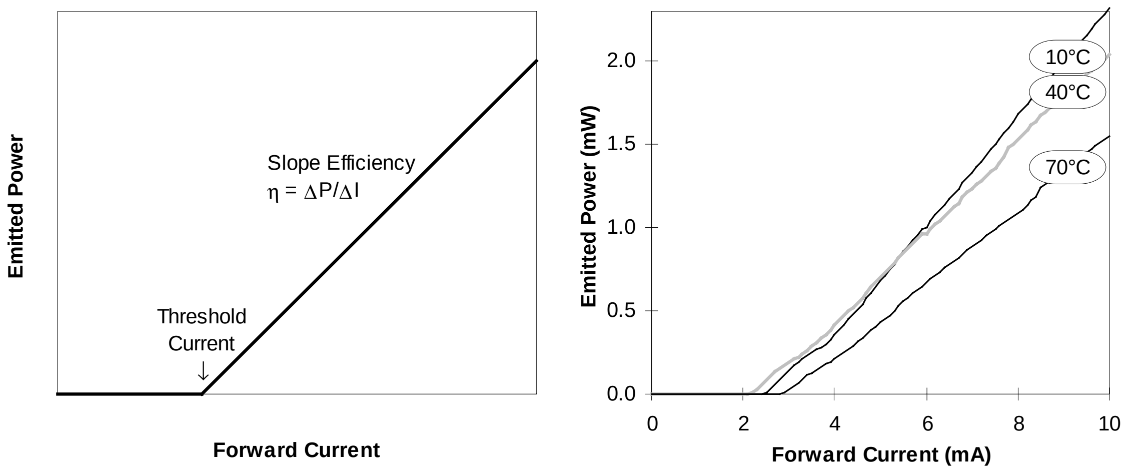

Figure 1. Definitions of I_{TH} and η and examples of temperature behavior. At high currents, above the specification limits, the power "rolls over," and subsequently decreases as the current increases.

Since many designers will not have used VCSELs before, and for purposes of comparison, we occasionally refer to "typical" edge-emitting lasers below. By this we mean the cleaved-cavity lasers that are used in large volumes. Specialized edge-emitters at higher costs can have different characteristics.

This note is organized into three major sections. The first describes some general properties of VCSELs and their temperature-dependence, the second deals with modulation characteristics of VCSELs, and the third shows how the temperature-dependence may affect the modulation and how to minimize those effects in example applications.

VCSEL Characteristics	
Characteristic	Symbol
Threshold Current	I_{TH}
Slope Efficiency	η
Series Resistance	R_S
Temperature at Minimum Threshold	T_0
Minimum Threshold over Temperature	I_0
Relative Intensity Noise	RIN

System Characteristics	
Characteristic	Symbol
One-Level Power	P_1
Zero-Level Power	P_0
Average Power	$\langle P \rangle$
Extinction Ratio	ER
DC Bias Current	I_{BIAS}
Modulation Current	$I_{MODULATION}$
Turn-On Delay	t_D

Table 1. Definitions of some symbols used in the text.

Temperature 1. Threshold Current Behavior

The lasing threshold current is determined by the difference between gain and loss at the lasing wavelength. The lasing wavelength in a VCSEL is determined by the Fabry-Perot resonance defined by its distributed Bragg reflector (DBR) mirrors (see the application sheet *850 nm VCSEL Products Reliability Study* for a brief description of VCSEL structure), and not by the wavelength with maximum gain. Because the gain peak of the quantum well emission and the resonance of the DBR mirrors change at different rates with temperature, the VCSEL I_{TH} is a minimum at some temperature, T_0, where the peak of the quantum well emission coincides with the DBR resonance. (Descriptions of edge-emitting lasers sometimes also refer to a T_0. In that case it applies to a different, and hypothetical, parameter which should not be confused with this VCSEL usage.) Note that each VCSEL may have a different value of T_0. From T_0 the threshold increases as the temperature is *either* raised or lowered. (This is very unlike a typical edge emitting laser, whose threshold monotonically and significantly increases as the temperature is raised.) The minimum VCSEL threshold current at T_0 is defined as I_0. The threshold current is found empirically to be parabolic with temperature, and can be fit to the approximate equation,

$$I_{TH}(T) \approx I_0[1.1\times10^{-4}(T-T_0)^2+1].$$

The graphs in Figure 2 show how the parabolic characteristic can lead to very low variations in I_{TH} near T_0, but to large variations far from T_0. In particular, note that regions of very flat behavior for one device may be regions where other devices show some variation. For *HFE*

VCSEL products, the I_{TH} typically does not increase or decrease more than 1 mA from its 25°C value.

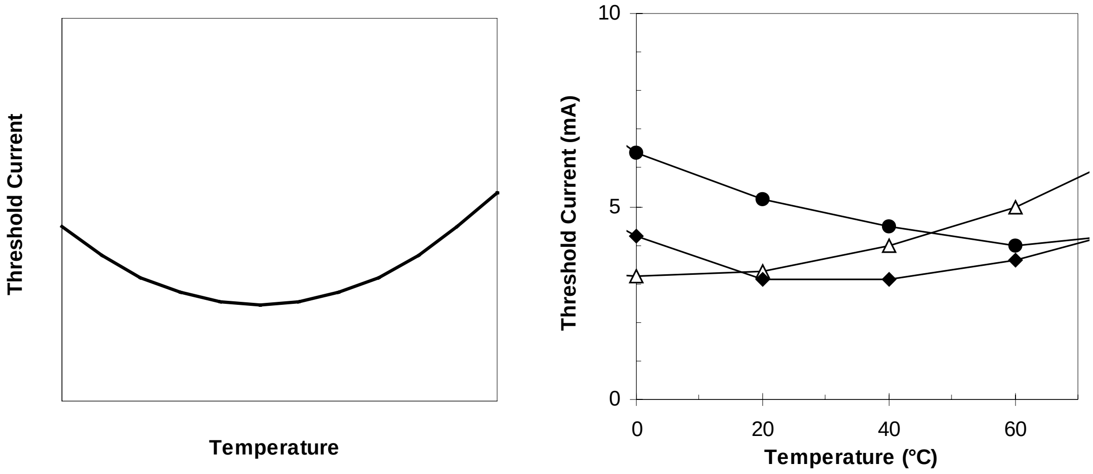

Figure 2. Threshold current variation with temperature. Characteristic parabolic shape is shown at left, several actual devices demonstrating the range of possible behaviors at right.

Temperature 2. Slope Efficiency Behavior

Above threshold the output power from a VCSEL varies approximately linearly with current. Slope efficiency is the incremental increase in power for an incremental increase in current. From the user's perspective it is not simply a function of the VCSEL chip—every source of power loss in the design, whether due to attenuation or to imperfect coupling, contributes to the effective value of η. The chip contribution is a function of the laser gain, material absorption, and mirror reflectance, all of which are themselves functions of temperature. Taken together, the resulting change in slope efficiency can be quite difficult to predict. In general, the slope efficiency decreases approximately linearly with temperature, as shown in Figure 3. This same effect occurs in typical edge-emitting lasers, though it is generally less pronounced.

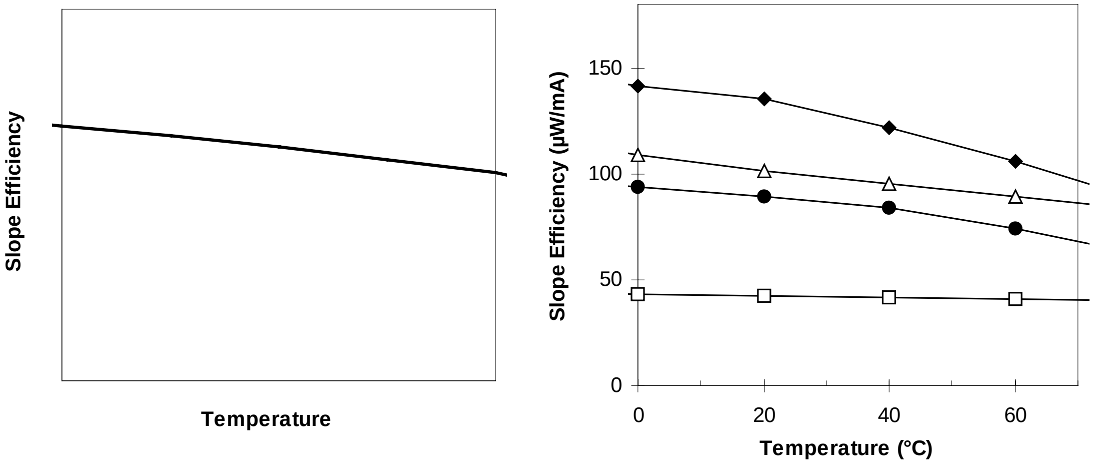

Figure 3. Slope efficiency variation with temperature.

Another way to describe the data of Figure 3 is incrementally, where the value at any temperature is the percentage by which η changed from that at the next lower temperature. Assuming linear change with temperature corresponds to assuming a constant incremental change, expressed as %/°C (where the percentage is of the value at one reference temperature, typically 25°C) or as ppm/°C (1%/°C = 10,000 ppm/°C). The errors introduced by such an assumption are small at moderate temperatures. Extreme behaviors from 0 to -10000 ppm per °C are possible, and -5000 ppm is typical.

Over a limited temperature range, slope efficiency can be approximated as,

$$\eta(T) \approx \eta(25°C)\times[1-(T-25)\times\Delta\eta/\Delta T].$$

If η is known at a temperature closer to the intended application temperature, T_A, use $\eta(T_A)$ and $(T-T_A)$ in the equation for more accurate results.

Temperature 3. Series Resistance Behavior

For most semiconductor diodes, the junction voltage at a fixed current decreases as the temperature increases. The VCSEL is no exception, with approximately a -1 mV/°C variation. Unlike the small impedances of many other diodes, however, the VCSEL *series resistance* cannot be ignored in circuit design. Typical VCSEL resistance is above twenty ohms, and the temperature coefficient of this resistance dominates the temperature dependence of the VCSEL current-voltage characteristics.

The DBR mirrors which make the VCSEL possible are composed of layers of alternating high and low-bandgap semiconductor material (see *850 nm VCSEL Products Reliability Study*). Each alternation produces a heterojunction with a small barrier potential. The high mirror reflectivities necessary for VCSEL performance require many, many such layers so even small potential barriers can add to form a significant voltage drop. Although it is not truly ohmic, it is reasonable to approximate this voltage drop as a resistance in series with the diode. This effective resistance *decreases* exponentially as the temperature increases

There is another series resistance component due to the bulk conductivity and its changes with temperature. For doped semiconductors, this component of resistance *increases* as temperature increases. The combination of the two effects can be modeled as a roughly linear decrease in series resistance as the temperature increases, but only over limited temperature ranges. Typical rates of change are -1000 to -5000 ppm/°C, with the greatest changes occurring at the lowest temperatures and in lasers with the greatest room-temperature resistance.

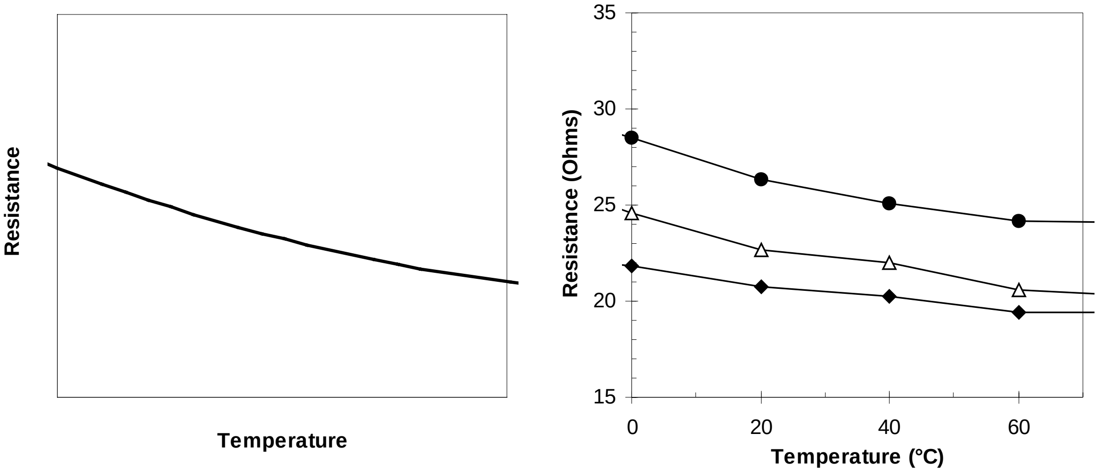

Figure 4. Series resistance variation with temperature.

There is no straightforward mathematical model that accurately predicts series resistance as a function of temperature. However, little error is introduced by,

$$R(T) \approx R(T_A)\times[1-(T-T_A)\times\Delta R/\Delta T]$$

where T_A and $\Delta R/\Delta T$ are defined in the same way as their slope efficiency counterparts.

While it is often acceptable to treat the series resistance as a single characteristic, as is done in Figure 4, sometimes it is more appropriate to deal with the different contributors to R_S separately. This is done explicitly in the later section on equivalent circuits.

Temperature 4. Emitted Power Behavior

How the emitted power of a VCSEL varies with temperature depends both on the VCSEL characteristics and on the driving circuit. Given a dc current source, the VCSEL power can be simply modeled as,

$$P(I,T) \approx \eta(T)\times[I-I_{TH}(T)].$$

This equation is valid up to a few mA below the rollover current, so it is approximately accurate throughout the operating current range. The results of such a calculation are shown in two sets of units, along with actual measured power, in Figure 5. As the right-hand graph in Figure 5 shows, for some VCSELs even this simplest circuit can maintain power within a range of a few tenths of a dB.

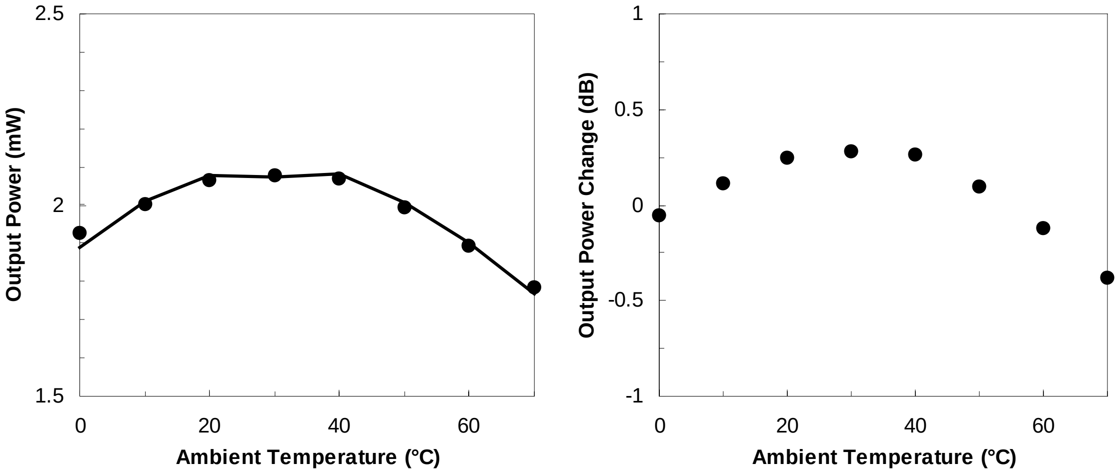

Figure 5. Measured (•) and modeled (–) power at 12 mA fixed current.

Parameter	Value	Units
η(25°C)	0.22	mW/mA
Δη/ΔT	-0.65	%/°C
T_0	45	°C
I_0	2	mA

Table 2. Values for Figure 5 sample calculations.

By appropriate selection of the operating point and the temperature coefficients of the driving circuit, the power can be maintained near a constant value or may have either a positive or negative temperature coefficient.

A few obvious principles will improve the stability of power over temperature in any design: operate far above threshold; compensate the average slope efficiency and series resistance temperature coefficients; and limit the temperature range as much as possible. Even better is to characterize each VCSEL and to compensate its behavior exactly.

Temperature 5. Reliability Behavior

VCSEL reliability compares very favorably with that of typical edge-emitting lasers and even with that of 850-nm LEDs. At room temperature and at moderate currents, VCSEL MTTF exceeds ten million hours. For a complete description of the variation of VCSEL reliability with temperature and current see the application note, *850 nm VCSEL Products Reliability Study* and the occasional reliability updates. Generally, reducing temperature improves reliability. Because the degradation activation energy is near 1 eV, the temperature-dependence is quite pronounced. Decreasing reliability with increasing temperature means that the application environment must be carefully considered, even if parametric performance variation over temperature is acceptable. Robust applications use the lowest operating current consistent with both adequate stability over temperature and proper modulation characteristics. In no applications should the currents exceed the data sheet maximum limits, generally 15 mA average or 20 mA peak current.

Modulation 1. Applicability

VCSELs can be modulated at speeds ranging from dc to several gigahertz. This sheet is intended to assist in digital applications several tens of megahertz and faster. At lower speeds, nearer the thermal time constant of the VCSEL (approximately 1 µs), different considerations apply and many of the effects described below become irrelevant. Generally, caution should be exercised when extrapolating characteristics measured near dc to multiple-megahertz or gigahertz frequencies. On the positive side, many artifacts of the power vs. current characteristics—sometimes called “kinks”—disappear at high modulation rates (see Figure 6). At very high rates, however, some data pattern dependence can emerge due to tails in the last 10% or so of the rising and falling edges.

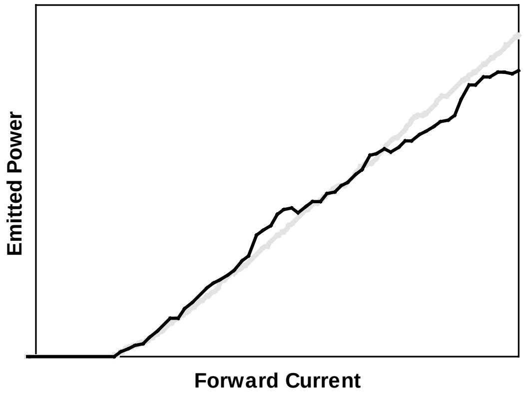

Figure 6. The power as current is swept slowly of a “kinky” VCSEL (black), and of the same device as current is swept at 100 kHz (gray). Note disappearance of kinks at high speed.

In addition, because of the transverse mode structure of the VCSEL, details of the optical coupling become very important. If the modes are not uniformly sampled, pulse rising edges exhibit complex structure and may either overshoot or be abnormally slow. In addition, some multimode fiber exhibits anomalously low bandwidth when the conditions of power launch on the fiber face are outside a narrow acceptable range. For these reasons, extreme care must be exercised in the design and execution of optics for fiber-coupling VCSELs (for more details, see Tatum, *et al*., in the references). Honeywell sells a range of pre-connectorized VCSELs to relieve the user from these complications.

Finally, we assume some familiarity with fiber optic data communication test procedures. General texts explaining those procedures in much more detail than the limited space in this sheet allows are available. The reference list includes one such: Derickson, *et al*.

Modulation 2. Relaxation Resonance

All lasers exhibit a relaxation resonance, which produces oscillation on the pulse rising edge. If this oscillation is too near the operating frequency or of too large a magnitude, it can severely limit laser performance. This is often the case in typical edge-emitting lasers. In the VCSEL, however, the relaxation resonance frequency is typically above 5 GHz and the amplitude of the resonance is so small as to be difficult to measure at all (see Figure 7). For typical applications of VCSELs, then, this effect can be ignored. There is a possible exception to this rule at very low modulation and bias currents, where the relaxation resonance frequency is lower (though even at low currents the VCSEL oscillation is usually well damped). This is one of several reasons not to operate VCSELs at too low modulation currents, at least not while very near threshold.

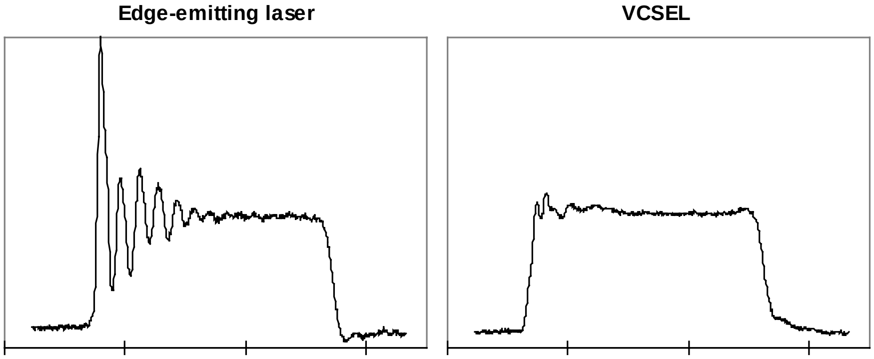

Figure 7. Comparison of edge-emitting laser and VCSEL optical signals into a wide-band receiver, showing effect of relaxation resonance. Time divisions are 1 ns.

Modulation 3. Optical Noise Sources

Relative intensity noise (RIN) is caused by the coupling of spontaneous emission from the laser into the stimulated emission. This causes unwanted fluctuations of the optical power, thereby generating a noise current in the optical detection circuit, which translates to an optical power penalty in the data link. RIN is measured into a finite bandwidth optical system, and is thus quoted in terms of dB/Hz. Because of their extremely high reflectivity mirrors VCSELs generally display less RIN than typical edge emitters. A typical value is less than -125 dB/Hz.

Another source of optical power noise is the feedback of stray optical reflections into the laser. This is an unavoidable effect common to all laser systems, and proper engineering of the optical assembly is required to minimize its effects. Honeywell offers a line of attenuated VCSEL components that provide enhanced isolation of the laser from optical back reflections.

The optical power in a multimode VCSEL is partitioned between several lasing modes, so modal noise can occur when one of the modes is discriminated. Polarization-selective elements, such as beamsplitters and some couplers, can also produce this kind of noise (see Tatum, *et al*., for more details). We recommend that, when coupling the emission into an optical system, the VCSEL lasing modes be uniformly sampled in order to prevent modal noise. Honeywell offers a line of pre-connectorized components to relieve the user from these complications.

Modulation 4. Turn-On Delay

If a VCSEL is operated such that the pulse zero level (which we'll call I_{BIAS}) is well above I_{TH} and the pulse one level (which is $I_{BIAS} + I_{MODULATION}$) at some higher current, the rising edge of the optical pulse trails the rising edge of the electrical pulse by only a few tens of picoseconds. If the pulse zero level is lowered, the difference increases and, varying with data rate and typically at some current well below I_{TH}, the rising edge delay becomes unacceptably large. Because this effect does not occur on the falling edge, the result is pulse width distortion.

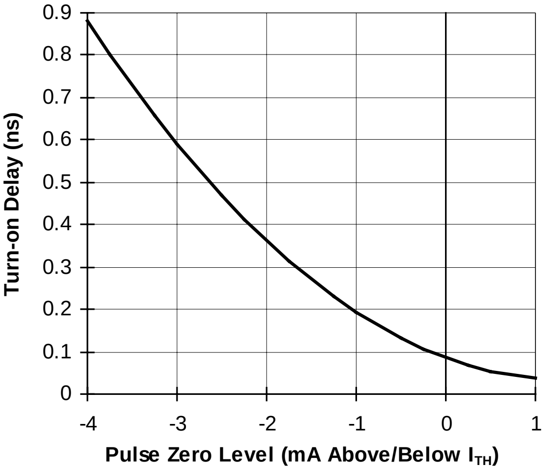

Figure 8. Turn-on delay as a function of distance from I_{TH}.

After each pulse, there is a rapid drop toward the pulse zero level. At high data rates, however, it may take more than one bit time for the last few percent to decay away. If a pulse is preceded by multiple zeros, it behaves as if it rose directly from the zero level. But if it is preceded by multiple ones and a single zero, the rising edge begins from a level above true zero. In other words, the distance from I_{TH} may be a function of the preceding data and thus the turn-on delay will vary from pulse to pulse. This results in data-dependent jitter of the rising edge. The most effective way to minimize this effect is to operate with the pulse zero current above I_{TH} or so near it that the resultant turn-on delay (and thus its variation) is very small.

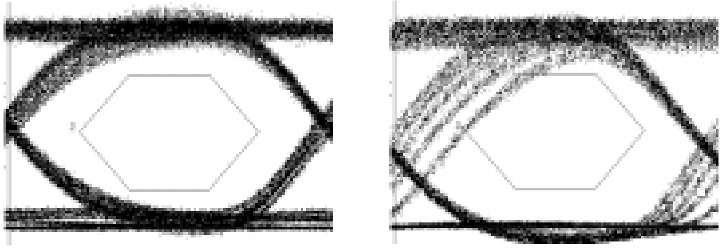

Figure 9. Eye diagram of a single VCSEL: properly biased (left) and biased too far below I_{TH} (right), with resulting jitter. (Fibre Channel K28.5 pattern.)

In general, turn-on delay sets a minimum acceptable I_{BIAS} relative to I_{TH}. When data rates or specifications allow, a fixed value of I_{BIAS} can be used for all VCSELs; otherwise, I_{BIAS} must be set for each VCSEL based on its individual I_{TH}.

Modulation 5. Off-State Bounce

The multi-transverse mode structure of VCSELs, so beneficial in reducing modal noise problems in fiber-optic applications, also results in the phenomenon of off-state bounce. The basic cause is that VCSEL modes are spatially separated and surrounded by regions which are forward-biased, but not lasing. When a lasing region is turned off, a charge carrier gradient is produced which draws carriers from the surrounding material, briefly raising the region back above the carrier density required for lasing. This produces a small power "bounce" up to several hundred picoseconds after the pulse falling edge. Depending on the VCSEL geometry and the speed of the driving circuitry, this bounce may be separated from the falling edge or may blend with it, increasing the apparent fall time. After passing through the filters (or limited-bandwidth receivers) required in many data communication standards, this blended behavior is all that can be observed, regardless of the actual transmitter signal.

Figure 10 shows a VCSEL transmitter pulse with a larger than usual off-state bounce component. Figure 11 shows the receiver eye diagrams for the same VCSEL, with and without bandwidth limiting. Note how the encroachment on the lower left corner of the eye disappears when the bandwidth is appropriately limited.

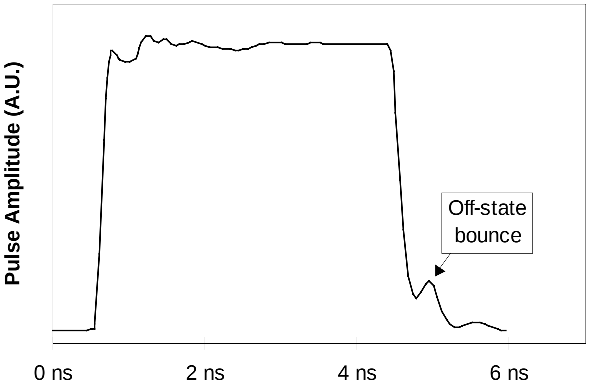

Figure 10. VCSEL pulse showing off-state bounce.

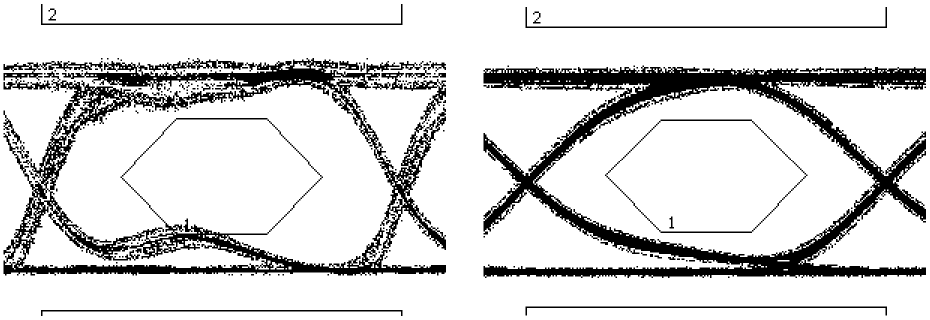

Figure 11. Receiver eye diagram without (left) and with (right) 937.5 MHz, 4-pole, Bessel-Thomson filter.

If the off-state bounce is found to limit performance, its effects can be minimized by increasing the modulation current. To a good approximation, the absolute magnitude of the off-state bounce does not increase with modulation, but that of the desired signal does, making the bounce a smaller fraction of the pulse one level. If the higher modulation unacceptably raises the average power, a VCSEL packaged to reduce the slope efficiency should be used. For applications where this is necessary, Honeywell's attenuated packages provide this feature.

Since the effect is basically due to charge storage, any technique which removes charge more rapidly when the laser is turned off can decrease the 80%-20% fall time. One such technique superimposes an undershoot of a few hundred picoseconds and a few mA on the falling edge of the driving pulse. So long as the VCSEL is operating at or above I_{TH} by the start of the following pulse, this also reduces the data-dependent jitter described above.

Modulation 6. Extinction Ratio

Extinction ratio (ER) is defined as the pulse one level power divided by the pulse zero level power. It is usually expressed in dB [ER in dB = $10\times\log_{10}(P_1/P_0)$], and dB units will be used in most examples below. By definition, ER can range from 0 dB (no modulation) to infinity (no zero-level power). The importance of a large ER is widely debated, particularly for ac-coupled receivers, but some level of ER is required for any system. One complication is that different instruments may measure ER differently (some may use average power levels, others may use levels after any ringing has died out; still other techniques are sometimes used). Measured ER may also vary with pulse width, so a fixed condition (generally a 125 MHz square wave) is used to provide repeatability. It will almost never be true that an ER measured between the dc zero and one levels will exactly match the ac ER for the same currents.

The power emitted by a VCSEL below I_{TH} is very low compared to the power even a small distance above I_{TH}. As a result, very large extinction ratios are possible if the zero level is held below I_{TH}. If ER were the only consideration, this would be the optimum operating regime: zero level well below I_{TH}, one level well above. And this kind of operation is possible at low enough data rates. Unfortunately, turn-on delay limits just how far—if at all—below I_{TH} one can operate. For typical high-speed systems, operation with I_{BIAS} at or very near I_{TH} is necessary.

Modulation 7. Equivalent Circuits

The equivalent circuit of a VCSEL contains elements associated with the chip and its package. Some of these elements, such as lead length, are under the control of the user; others are internal to the package. There will usually be other parasitic components, such as pad capacitances and trace inductances, that are also under the user's control. Those should be added to the equivalent circuit shown below before modeling. Unfortunately, we know of no single large-signal equivalent circuit that can adequately represent the VCSEL both above and below threshold. For more information on laser modeling see Lau and the references therein.

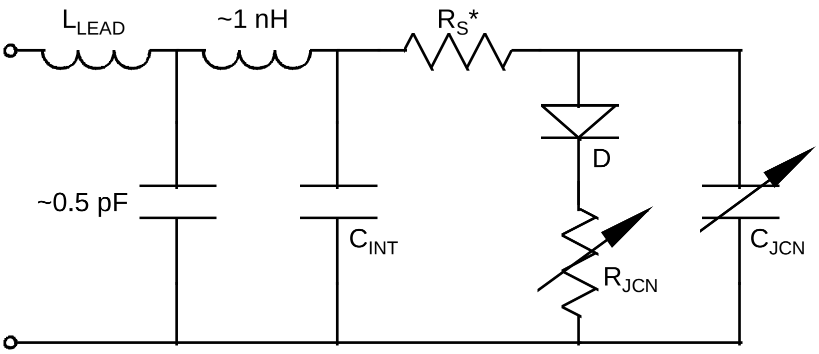

Figure 12. Equivalent circuit of packaged VCSEL. L_{LEAD} is 0.2-2 nH, depending on lead length; C_{INT} is 0.8-2.5 pF, depending on package; D is a perfect diode with 1.45 V drop; R_{JCN} and C_{JCN} vary as described below; and R_S* is data sheet R_S minus 10-mA value of R_{JCN}.

The equivalent circuit above is appropriate below I_{TH}. Above I_{TH}, the voltage across the diode (D and R_{JCN}) is approximately clamped and C_{JCN} should be removed from the circuit (other elements may be added to simulate the light emitted above threshold; for details, see Harder, *et al.*, in the references). The values of R_{JCN} and C_{JCN} are complicated functions of the VCSEL geometry and bias effects. The graphs of Figure 13 show their approximate values. They are not strong functions of temperature.

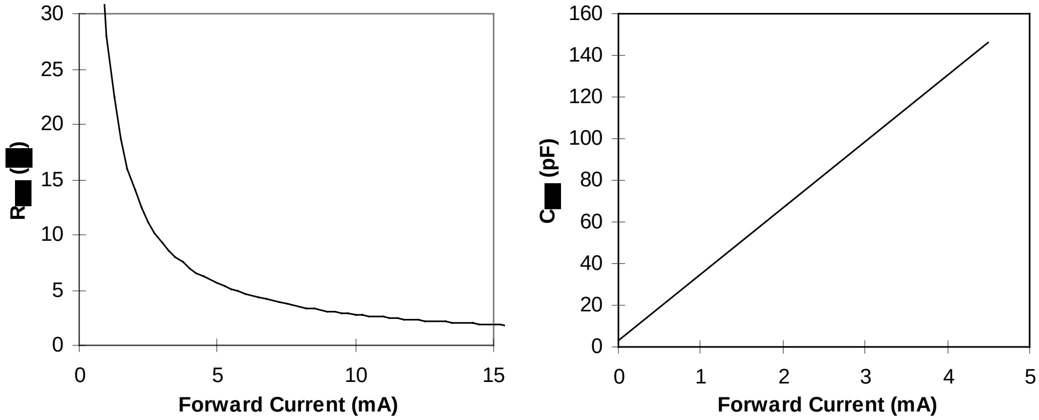

Figure 13. Approximate junction resistance and capacitance as a function of forward current. Above I_{TH}, the capacitance becomes negligibly small.

Modulation 8. Rise and Fall Times

It might seem surprising that the rise and fall times should be left until last in a discussion about modulation characteristics, but they are generally not performance limiters. VCSELs can have small-signal bandwidths well over 5 GHz and large-signal 20-80% rising and falling edges faster than 100 picoseconds if driven appropriately. (VCSEL edge speeds are generally given as 20-80%, rather than 10-90%, values because the first and last 20% may be slowed somewhat by carrier distribution and mode partition effects. Since these slow tails do not affect the switching in typical data communications applications they are excluded from the useful edge speed measurement.) As described above, edge speed can be increased with charge-control through appropriate peaking of the drive current. In practice, however, turn-on delay—through its influence on jitter—is the primary limiter of high-speed performance, with some of the other effects mentioned above contributing if the VCSEL is inappropriately driven.

Modulation 9. “Eye-Safety”

As turn-on delay sets an effective minimum for I_{BIAS}, the laser safety classification sets an effective maximum for $I_{MODULATION}$. There are several standards, with different test methods and requirements, but there is always a maximum allowable average power for each classification. More information on these standards is available in the application sheet, *Laser Safety Requirements for Users of Honeywell’s VCSEL Products* and in the standards themselves. For purposes of this modulation application note, we use examples which demonstrate how $I_{MODULATION}$ is limited by the laser classification, but we do not (and cannot) provide specific guidance for achieving any particular classification.

Putting It All Together 1. Considerations Common to All Driving Schemes

The good news is that none of the modulation parameters discussed in the Modulation section of this note are direct functions of temperature. They are, however, functions of the characteristics that do change with temperature—principally I_{TH}, η, and R_S.

To properly balance the design of extinction ratio and turn-on delay jitter, it is necessary to bias the VCSEL close to threshold, typically with less than 0.5 mA difference between I_{BIAS} and I_{TH}. This is complicated by the parabolic nature of the VCSEL threshold current over temperature. Some relief is provided to the designer in that Honeywell VCSELs used in data communications will have less than ±1 mA change in threshold over the 0 to 70°C operating range.

Very small modulation currents—less than about 4 mA—are generally a bad idea. The sensitivity to temperature and lifetime degradation is enhanced when a small change in I_{TH} is a large fraction of the starting $I_{MODULATION}$, and highest-speed performance also requires higher modulation.

The slope efficiency of the complete optical system—VCSEL, optics, and alignment—determines the required modulation current. It is usually not acceptable to lower the effective slope efficiency by intentionally misaligning or defocusing to decrease coupling because, as described above, such schemes lead to anomalous optical waveforms. Honeywell offers a range of parts with slope efficiency adjusted through uniform attenuation of all modes, affording appropriate power and modulation for various applications without risking the consequences of improper coupling.

The primary importance of series resistance to high-speed systems is its effect on impedance-matching. The VCSEL driver is designed for a particular impedance, whether directly attached or at the end of a transmission line. In either case, if the VCSEL, line, and driver are not matched, the interactions lead to anomalous wave-forms. Just how well matched the system must be depends on many factors, but it is wise to aim for no worse than a 10% mismatch. (We have found some driving systems with no significant waveform anomalies with impedance mismatches in excess of 50%, but these are the exceptions, not the rule.)

In this section, we need to define some simple algebraic relationships between the optical power and the modulation and bias current. Those described below are appropriate for dc-coupled driving schemes. For a laser, the optical power increases linearly above threshold, and below threshold the power can be approximated as a constant. Mathematically, this is described as;

$$P_1 \approx \eta(I_{MODULATION}+I_{BIAS}-I_{TH})$$

$$P_0 \approx \eta(I_{BIAS}-I_{TH}) \quad \text{for } I_{BIAS}>I_{TH}\text{; approximately zero otherwise}$$

The extinction ratio is defined as the log of the ratio of optical power in a logic one to the optical power in a logic zero,

$$ER = 10\log(P_1/P_0)$$

In most closed loop systems, the average power is used as the control variable, and it is defined as the mean of an optical one and an optical zero;

$$\langle P\rangle \approx (P_1+P_0)/2$$

Finally, for calculation purposes, we define an analytical expression for the turn on delay (in ps) which is only valid for currents below threshold to no more than 1.5 mA above threshold;

$$t_D \approx 30(I_{BIAS}-I_{TH})^2-80(I_{BIAS}-I_{TH})+90$$

All the above relations are functions of temperature since I_{TH} and η (and possibly other parameters) are temperature-dependent. The nominal conditions for the examples below are given in Table 3. (Note that each VCSEL is different, this is an example only.)

Parameter	Value	Units
$I_{BIAS}(40°)$	$I_0+0.5$	mA
$I_{MODULATION}(40°)$	10	mA
$\eta(40°)$	0.1	mW/mA
$\Delta\eta/\Delta T$	-6000 -0.6	ppm/°C %/°C
T_0	40	°C
I_0	4	mA

Table 3. Parameter values used in examples.

Data communications designs generally account for degradation of emitters over the operating lifetime by including an allowance in the optical power budget. The appropriate allowance depends on many factors, including the operating point, operating environment, expected system life, and others. Honeywell uses a lifetime allowance of +1 dB and -2 dB change in power, but there is nothing magic about those numbers.

In any design, one must decide how to tolerance the various contributors to variation; the choices are usually worst-case or RSS (Root Sum of Squares, a statistical tolerancing system). This can be an important issue in data communications, where optical budgets are often tightly constrained, but where physics imposes limits on minimum economical variation. Except where safety is concerned, it is invariably best to use an approach that explicitly considers the improbability of several characteristics simultaneously adopting their most disadvantageous values. Another required design decision is whether to characterize components and adjust the values of circuit elements in each assembly for optimum performance. The advantages are obvious, but significant additional cost may be incurred in the characterization process, necessitating a careful tradeoff.

In the following three sections, we will provide examples of three common driving schemes, which are broadly categorized as either open- or closed-loop. In no example has circuit temperature compensation been employed, though for real designs we always recommend such compensation. Significant improvement in performance can be achieved when the circuit compensates for the nominal temperature variations. For each case, we provide the extinction ratio (in dB), average power (in mW), and turn on delay (in ps) as a function of temperature. In a real design the values each of these characteristics take must be compared with specification limits. It should be noted that the graphs represent one particular VCSEL, and device-to-device variations must be accounted for in a specific design. In an open loop configuration, the details of the laser at any particular time are unknown, and there is no active compensation for the laser properties as the environment or physical properties of the laser change. Closed loop schemes can provide a change in either the bias current or the modulation current to maintain a constant optical power over both time and environment (these techniques are frequently abbreviated MPC, for “Mean Power Control”). Each of the schemes has relative merits, and we will attempt to point out strengths and weaknesses of each design below. This list of designs is not exhaustive, and our examples may not represent the best possible configuration for a particular design. Finally, though perhaps it should go without saying, we offer application assistance—but we cannot provide specific designs for specific applications. The examples below illustrate the principles involved in establishing a data communications transmitter design, but are not actual designs for any particular use.

Putting It All Together 2. Open-Loop Operation

In open-loop operation no information about the current state of the VCSEL is available. Thus all the possible variations in VCSEL behavior over time and temperature must be accommodated by the optical budget and the fixed circuit characteristics. If the budget is wide enough, detailed knowledge about each VCSEL may be unnecessary. But if, as is more typically the case, the optical budget is severely constrained, the circuit set-up will be unique for each VCSEL. To assure compliance with the budget, at least four things must be known: I_{TH} and η at some temperature, and how each varies as the temperature is changed.

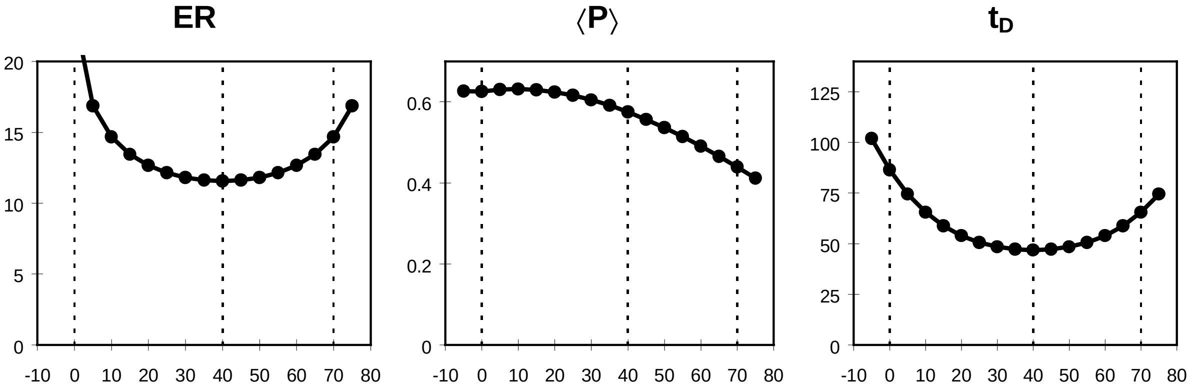

Figure 14. Extinction ratio, average power, and turn-on delay for open loop operation example.

Open loop configurations provide the simplest conceptual design. If appropriate temperature compensation is provided in the driving circuit, even better performance is achievable. In those cases where the optical budget is severely constrained, the electrical driving circuit must be customized for each VCSEL.

A variant of this technique is to use a monitor photodiode, but only to provide a maximum eye-safety power shut-off, not in a continuous control loop.

Putting It All Together 3. Mean Power Control by Adjusting Bias Current

Historically, a monitor photodiode packaged with the laser has been used to provide the control signal for the laser. In an ideal world, the feedback on optical power would be from the signal detector at the other end of the fiber. In either case, the feedback control signal is used to maintain a constant average power from the laser by adjusting I_{BIAS} and keeping $I_{MODULATION}$ fixed (performance is the same whether modulation is dc- or ac-coupled).

Because the threshold current in typical edge emitting lasers is very temperature dependent, this is the only way they can be used in data communications applications. Mean power control by adjusting the bias current works best when the dominant change in the optical power is caused by changes in the threshold current and not slope efficiency. In VCSELs the change in slope efficiency over temperature usually dominates the change in optical power. The performance of a typical VCSEL in a MPC circuit is described below.

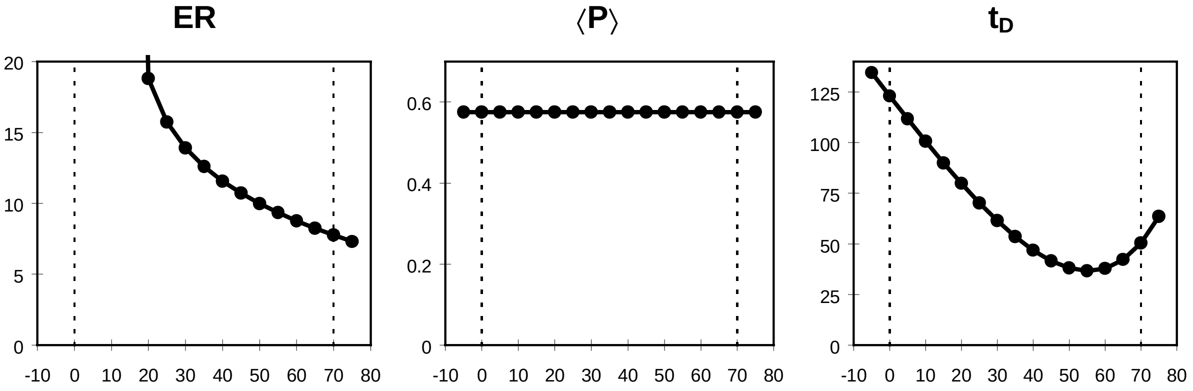

Figure 15. Extinction ratio, average power, and turn-on delay for I_{BIAS} MPC operation example.

MPC by definition controls the average optical power, thereby making it easier to eliminate environmental and aging properties from the optical link budget However, MPC does not compensate the changes in extinction ratio or turn on delay, and these may be the performance limiters of the optical link. As the example demonstrates, appropriate compensation of the temperature dependence of slope efficiency may be necessary to meet the requirements of the optical link budget.

Putting It All Together 4. Mean Power Control by Adjusting Modulation Current

Data communications was dominated in the past by typical edge emitting lasers, and the change in optical power over both time and environmental variables was dominated by the change in threshold. Therefore, control of the optical power by adjusting the modulation current was not a popular approach. With VCSELs, this method may become more attractive to the designer, particularly when the modulation currents are large compared to the bias current. The following example demonstrates the performance of a typical VCSEL in a MPC circuit where only the modulation current is being adjusted.

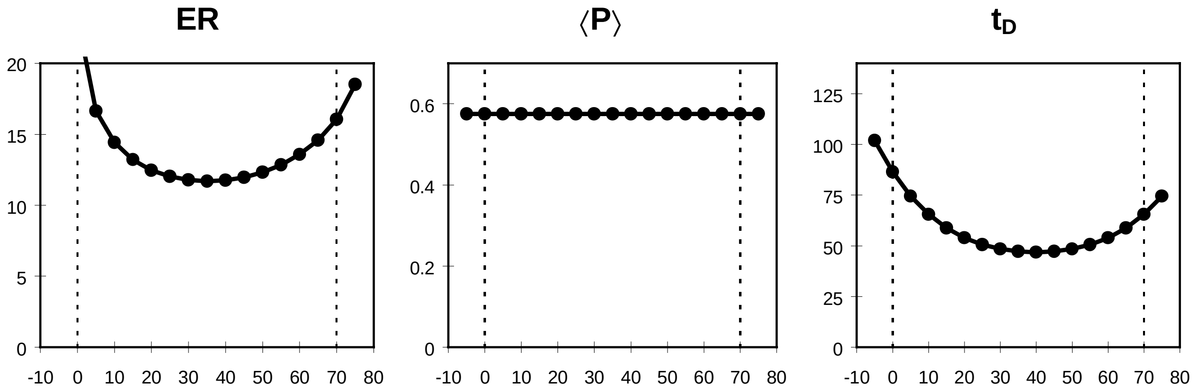

Figure 16. Extinction ratio, average power, and turn-on delay for $I_{MODULATION}$ MPC operation example.

This example assumes that $I_{MODULATION}$ is added to I_{BIAS}. Performance of the MPC circuit is not as good when the modulation current is ac-coupled into the laser with a bias-T. In the ac-coupled case, changes in the modulation current also cause changes in the effective I_{BIAS}, causing it to deviate significantly from I_{TH}. The analysis of the ac-coupled modulation case is similar to that above, except that one centers $I_{MODULATION}$ about the "half-on current" (equal to I_{BIAS} plus one half of $I_{MODULATION}$).

Typical Values

Values for most parameters are provided on the appropriate device data sheets. Some values that are not specified, but that might affect designs over temperature, appear in Table 4. The ranges are provided here for preliminary design feasibility analysis only. While they cover the majority of the distribution, they are not guaranteed and cannot substitute for application testing.

Parameter	Typical Values	Units
T_0	0 to 70	°C
I_0	2.5 to 5	mA
$\Delta\eta/\Delta T$	-0.2 to -0.85	%/°C
$\Delta R/\Delta T$	-0.15 to -0.4	%/°C
$\Delta I_{LPD}/\Delta T$ (monitor photodiode current at a fixed power)	-0.15 to 0.25 (depends on package)	%/°C

Table 4. Typical ranges of some VCSEL parameters.

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February 1998

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