A plot twist: the continuing story of VCSELs at AOC

James K. Guenter*, Jim A. Tatum*, Robert A. Hawthorne III, Ralph H. Johnson, David T. Mathes,
Bobby M. Hawkins
Advanced Optical Components, 830A East Arapaho Road, Richardson, TX 75081

ABSTRACT

During a year of substantial consolidation in the VCSEL industry, Honeywell sold their VCSEL Optical Products Division, which has now officially changed its name to Advanced Optical Components (AOC). Both manufacture and applied research continue, however. Some of the developments of the past year are discussed in this paper. They include advances in the understanding of VCSEL degradation physics, substantial improvements in long-wavelength VCSEL performance, and continuing progress in manufacturing technology. In addition, higher speed serial communications products, at 10 gigabits and particularly at 4 gigabits per second, have shown faster than predicted growth. We place these technologies and AOC's approach to them in a market perspective, along with other emerging applications.

Keywords: VCSEL, vertical cavity surface emitting laser, reliability, ESD

1. INTRODUCTION

"The more things change the more they stay the same." -Alphonse Karr

2004 was another year of tremendous upheaval in the data communications components industry. The landscape changed with the demise of several companies, acquisitions and mergers, and even a few new entrants. In Fibre Channel, the 4G product moved from idea to production in record time, challenging the supply chain to keep up with the burgeoning requirements for this new data rate. 850-nm 10G products also moved to production status with significant growth, surprising many pundits.

Nevertheless, despite the return of an industry pattern of modest growth, few companies in the transceiver or component industry made money. The demand by systems manufacturers for steadily decreasing prices, and willingness of manufacturers to succumb to the pressure, continued unabated. Reliability issues still haunted some users and manufacturers. The promise of 1310nm VCSEL technology continued to be ballyhooed but large volume production shipments were still a future-tense proposition.

In the "plot twist" of the title, the VCSEL Products Division of Honeywell certainly felt the effects of change in 2004 as well. In a deal announced just before the 2004 Photonics West Conference and closed in March of 2004, Finisar purchased the group from Honeywell and renamed it Advanced Optical Components, or AOC. Finisar had been the first customer for the Honeywell VCSEL in 1996 (in fact, the first true commercial sale of a VCSEL component was from Honeywell to Finisar) so the acquisition actually represented a continuation of a long-term relationship between the two. Despite this change of ownership, the VCSEL group stayed very much the same. AOC maintained the same location, customer set, and product portfolio as before (some still call it "The Honeywell VCSEL"). The management team and design staff remained completely intact throughout the transition (indeed through the entire year of 2004), and the focus on product reliability remained unchanged.

In that vein work continues unabated at AOC to better understand the reliability physics and failure mechanisms of VCSELs, and to use this knowledge to improve the design and processing of its products. In 2004 significant investment was focused on the continuing issue of EOS (electrical overstress) and ESD (electrostatic discharge) damage to VCSEL products. We describe some results of that work here, as well as show updated reliability studies for oxide-isolated VCSELs, repeating the legacy of continuing reliability improvement previously shown for the proton-implanted

* jim.guenter@adopco.com (972) 792-1826 or jim.tatum@adopco.com (972) 792-1870

device. Additionally, the production launch of 850-nm 10G components has necessitated overcoming many challenging issues, some of which we will discuss. 1310nm VCSEL development continues as well, with very promising results.

While 2004 was full of industry upheavals, at AOC we still work to invest in our manufacturing capabilities and continue our commitment to automation as a source of variation reduction. Die attach and wire bond precision and speed have both been upgraded with new equipment. The welding operation for TO cans, which used to be only partially automated, is now fully so. As part of our new product introductions at 4G and 10G, we have implemented a procedure allowing variable attenuation of TOSA slope efficiency, so that all parts can be driven at currents that provide the best speed performance at all temperatures. The venerable DOS-based wafer mapping software we used throughout our first VCSEL decade has finally been replaced with an even more capable custom data analysis tool. And finally, we have further improved our failure analysis capabilities, bringing FIB (focused ion beam) in-house. All of these activities aim toward continuing reliability improvement, enabling deployment of ever more VCSELs in ever more applications; some of the results of such a committed approach appear in the sections below.

2. MARKET PERSPECTIVE

In retrospect, 2004 may be seen as the year that the clouds began to clear over the turbulent telecom industry, and as a year of change for VCSEL technology. No, the long anticipated widespread adoption of 1310-nm VCSELs has not occurred, but there have been significant movements in the market. As we first discussed in reference 1, consolidation of the market has continued in earnest. Industry consolidation, and some attrition, has continued to decrease the number of pure play VCSEL companies (the former Honeywell VCSEL Products Group being one example), and arguably has left fewer than a handful of viable VCSEL suppliers remaining. The declining number of suppliers can be directly related to the continued pricing pressure at the optical transceiver product level, which has declined more than 75% in the last 5 years. Pricing pressure has not been the only determining factor, of course, as the requirements for performance and reliability have also been raised.

While 2004 heralded the launch of a high volume VCSEL application outside of data communications, the greatest volume continues to be driven by datacom. The total 850-nm VCSEL market opportunity in datacom is approximately 11 million devices, growing at a roughly constant rate for the next two years.[2] Growth is generally expected to continue on this pace. To date, the overall sensor market has paled in comparison, but does hold the opportunity to deploy a similar quantity of VCSELs in 2005. Still, even with this fantastic growth, the overall VCSEL component segment will remain under $100M in total revenue. Once again, this points to the long term economic viability of only a handful of suppliers.

2.1 The Data Communications Industry

With great fanfare, products supporting 10 Gbps Ethernet and Fibre Channel operation were introduced in 2004. The market forces were pulling for the adoption of the XFP form factor, primarily driven by the desires of the SAN community. However, the adoption of 10 Gbps Fibre Channel stalled for multiple reasons, including (1) the lack of available storage media supporting the interface speed, (2) difficulty in manufacturing electrical boards operating at these speeds, (3) the need to completely change the Fibre Channel interface and lack of backward compatibility, (4) the lack of market need, and (5) the relatively high price of the optical components and lack of widespread availability. Thus, the Fibre Channel market retrenched to introduce optical components operating at 4 Gbps, which did offer backward compatibility, modest price increases, and generally available storage devices. In fact, there is now a considerable push in the Fibre Channel standards group to develop an 8 Gbps solution that again preserves backwards compatibility. In the Ethernet and Sonet application space, the lion’s share of adoption has been long haul networks, typically 10 km or more, with shorter distance interconnect and “jumper” links now beginning to be deployed in the switching fabric. It is estimated that 850 nm data links will represent the majority of 10G volume in 2005 and following. One problematic area for the adoption of 10 Gbps Ethernet has been in the coverage of previously installed multimode fiber links up to 300 m in length. The original Ethernet standard provides coverage of these links with a Coarse Wavelength Division Multiplexed (CWDM) solution centered around 1300 nm. While a technically appealing solution, it has struggled with commercial adoption and generally lacks the widespread vendor support to drive development and cost reduction. Hence, considerable interest has emerged in extending the coverage of installed multimode fiber with single wavelength serial solutions that utilize EDC (electronic dispersion compensation) in the optical receiver to mitigate the low bandwidth of the optical channel. EDC is common practice with copper based interconnects, but is seldom used in optical interconnects. Significant challenges exist in developing a model for the fiber transmission medium, and understanding the “worst case” optical fiber and laser launch conditions. While it is widely anticipated that the achievable link lengths can be significantly increased, it is not expected to guarantee coverage out to 300 m on all of the installed multimode optical fiber. EDC is also an option under consideration with the Fibre Channel organizations to extend operation distance at 8 Gbps.

2.2 Other Applications

There have been VCSEL products for consumer applications in the past, but they were released by relatively small players and never led to enormous volume.[3] In 2004, however, a major player brought VCSELs into an optical mouse, with Logitech deploying a VCSEL based device. The performance of the VCSEL based solution relative to the traditional LED mouse is reported to be significantly improved. The major area of improvement for the VCSEL based solution is the ability to work on more surfaces; specular and repetitively patterned surface were particularly challenging for LED based mice. It would appear that VCSELs are poised to be significant players in the optical mouse market in the near future.

The Automotive industry has also begun to realize the value of the VCSEL in entertainment distribution networks based on the Media Oriented System Transport (MOST) standard. Traditional MOST systems are deployed using Plastic Optical Fiber (POF) and red LEDs. However, limitations of both the POF and LEDs, such as limited temperature ranges, large bend radius, and high connector losses have forced the automotive industry to consider the adoption of large-core glass optical fiber. The VCSEL is a natural fit for this application, and can be used reliably even up to 125°C environments.

To open up other areas of application for the VCSEL, several technical hurdles are yet to be solved reliably and inexpensively enough for mass production. These include the development of polarization stable VCSELs, high power (10 mW and greater) single mode VCSELs, and development of new VCSEL wavelengths such as 650 nm devices for optical sensing, and 1310-1550 nm VCSELs for continued expansion in the data and telecommunications networks.

3. VCSEL RELIABILITY UPDATE

Last year, preliminary data suggested that substantial improvements had been made in AOC oxide VCSEL reliability.[4] This year, with additional samples and the accumulation of additional burn-in hours, it became possible to update several of the oxide VCSEL reliability models. Just as AOC proton implant VCSEL reliability improved steadily, reduced variation, process improvements, and judicious specification tightening drove real improvements in oxide VCSEL reliability, so for many of our oxide designs the wearout reliability we predict today is nearly an order of magnitude higher than it was only two years ago. (The same cannot yet be said about random failure reliability, but see the comments in the ESD section below.) Even given further improvements in proton VCSEL reliability in the last two years, most of the AOC oxide designs now have reliability at moderate temperatures within a factor of two of the proton “gold standard.” Figure 1 shows that, at their nominal operating currents (different for each design, of course), wearout time to failure varies only a factor of two for designs as different as a 10G small aperture oxide and the proton implanted VCSEL. Of course the wearout reliability was already quite good, with typical times to 1% failures at 40°C measured in the millions of hours, or hundreds of years. But at higher temperatures, which also often necessitate higher drive currents, these kinds of improvements open new applications, those where worst

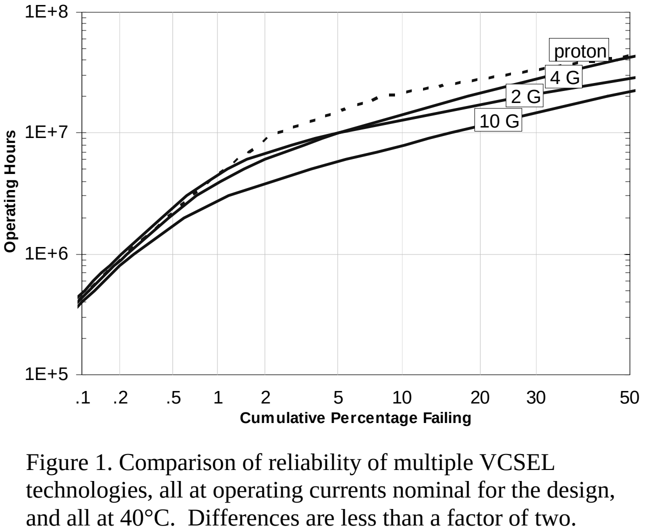

Figure 1. Comparison of reliability of multiple VCSEL technologies, all at operating currents nominal for the design, and all at 40°C. Differences are less than a factor of two.

case conditions might previously have precluded use of oxide VCSELs. Or they ease the minds of designers who wanted twenty years to 1% failures at 95°C operation, just in case, when our previous results might have only justified fifteen years. As described below, improved reliability may also allow redefinition of the failure criteria, making applications more sensitive to small changes in VCSEL characteristics possible.

Figure 2 shows the updated reliability models and compares them to those they replace. Except for the single mode VCSEL, each is identified by the approximate maximum data rate the particular VCSEL design currently supports. All predictions use the typical bias current for that design at the listed data rate.

While at high temperatures the reliability of well-made VCSELs is controlled by the wearout behavior regardless of operating duration, at moderate stress conditions, and in the first year of operation, the failure rate of AOC VCSELs is still dominated by random failures. (Random failure is indicated by the curvature to the left in these lognormal probability plots.) Improvements in wearout reliability performance have no effect on these random failures, so what strategy can we employ to obtain significant reliability improvement under these conditions? There is such a strategy, as the next section, and particularly Figure 8 makes clear.

4. ESD IN VCSELS

In most applications, most VCSEL failures in the first year of use are due to ESD. (Throughout this discussion, we will use the term ESD for both electrostatic discharge and EOS, distinguishing between the two only when necessary for clarity.) Circumstantial supporting evidence, at least for AOC VCSELs, has been presented previously, and there is wide agreement that ESD is a leading cause of failure for VCSELs and for semiconductor devices generally.[4-7] This continues to be the case today, *despite the fact that most participants at all assembly levels believe they use good-to-excellent ESD control procedures*.

How certain can we be that failures are caused by ESD? It is often the case that it is easy to diagnose failures that are *not* caused by ESD, but harder to prove when failures *are* caused by ESD. This is because most other failure causes leave visible external evidence of their existence, but ESD remains hidden deep inside the VCSEL. EOS failures may be exceptions to the ESD invisibility rule, because the melting, delamination, and even miniature explosions that result from EOS sometimes show on the VCSEL surface. If a VCSEL has current-voltage and

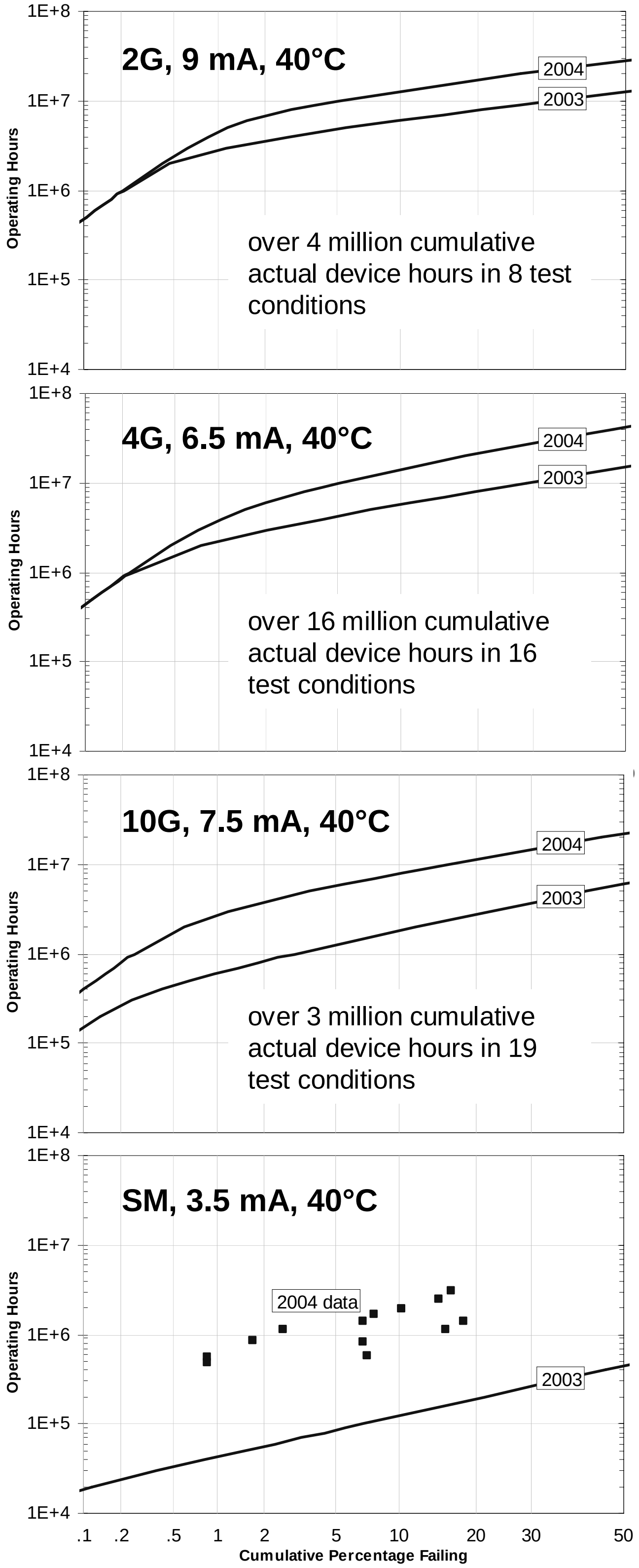

Figure 2. Updated reliability results for various AOC oxide VCSELs. Single mode data is not sufficiently complete for model update.

emission microscope characteristics consistent with dislocation degradation, but SEM (scanning electron microscope) and visible microscopy do not reveal a defect source, most types of failure causes can be ruled out.[8] (Most epitaxial defects and manufacturing damage, for example, would be visible if present.) Only dislocations threading from the mirrors or ESD remain as a potential failure causes. To separate these two possibilities is difficult, time consuming, and destructive—it generally requires TEM (transmission electron microscopy), which in turn requires preparation of a thin (typically less than 1-μm thick) membrane containing the defect. TEM analyses usually can determine if a failure was caused by ESD, without ambiguity.

In 2004, AOC undertook to establish just what fraction of verified oxide VCSEL field failures were due to what causes. While our field failure rate is small, generally about 10 ppm, our large volume of VCSEL shipments still affords more candidates for detailed failure analysis than the overworked failure analysts would prefer. Figure 3 summarizes the results of the analyses: more than 95% of all field failures were consistent with ESD—except for those with clear EOS damage, most had dislocation failure signatures without visible evidence of failure cause. As mentioned above, ESD might not be the only cause consistent with the microscopic and electro-optical data, so TEM was performed on a substantial number of the parts where failure cause could not otherwise be certain. The result again was that 95% were confirmed as caused by ESD.

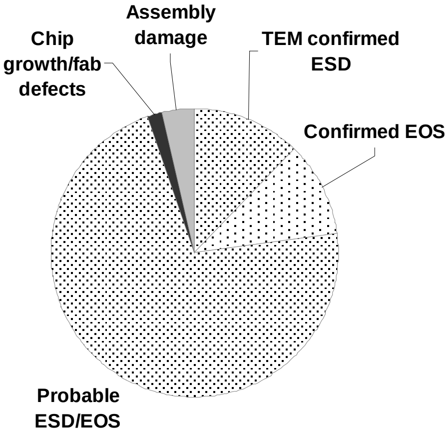

Figure 3. VCSEL field failure analysis for 2004, showing majority of failures are due to ESD.

With most VCSEL manufacturers and users maintaining controls in their factories that should protect devices with 100-V or lower ESD damage thresholds, why do we still see ESD damage as the primary cause of early failures? One probable reason is that when the phenomenon we are observing has an incidence measured in single-digit ppm, the standard process is not the issue. Rather it is the rare exception, where a procedure is violated "just this once," or where a part that should have been discarded as a result of such a violation is accidentally grouped with unexposed parts instead. There is a more fundamental reason, however: 100 V is not good enough. Most ESD control systems are based on HBM (human body model) ESD. Wrist straps, conductive floors, shoes, chairs, and smocks are all examples of attempts to control exposure through direct contact with charged human beings. Most also recognize that MM (machine model) ESD events require lower potentials to be damaging. For VCSELs the machine model damage threshold is almost always substantially less than 100V.[6] CDM (charged device model) ESD events are often overlooked, a big mistake for VCSELs, where many assembly types and processes make such events quite probable, where CDM damage thresholds may be below 20 V, and where their consequences can be especially insidious.

The simplified schematic model of Figure 4 shows several paths through an oxide VCSEL that are available to an ESD "zap." The capacitor and resistor shown at the extreme left represent parasitics for completeness, but almost no current ever flows through them. The rest of the model, overlaid on a partial VCSEL cross-section, includes the conducting aperture and the oxide that forms it. While the oxide is a good insulator at dc, at high enough edge speeds its impedance becomes small, and substantial current can flow even in the leftmost diode. For slower pulses, nearly all of the current flows through the diode at the right, in the center of the VCSEL aperture. Where damage occurs is thus a strong function of the speed of the pulse, with fast pulses typically causing damage due to dielectric breakdown in the oxide at larger radii, and slow pulses causing damage near the oxide aperture tip for pulses of moderate speed or near the

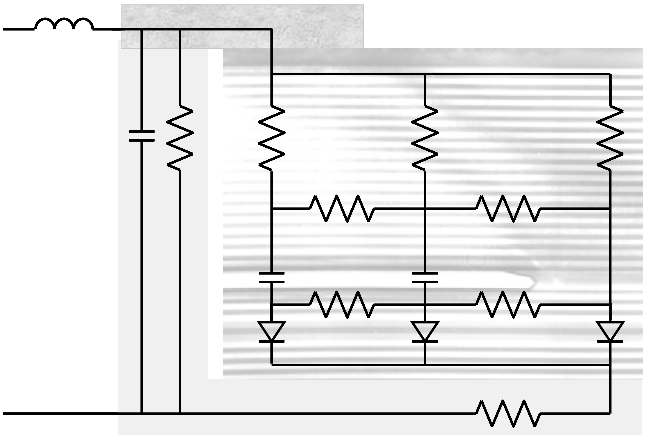

Figure 4. Lumpy electrical model superimposed over one side of an oxide VCSEL. Aperture center is at right.

center of the device for very slow pulses (the latter corresponding to EOS events, which we loosely define as those lasting near to or longer than the VCSEL’s 1-2-µs thermal time constant).

Each of the three ESD models has a corresponding circuit and defined pulse characteristic. For purposes of the results we will show subsequently, the three models were as shown in Figure 5. The values of voltage chosen for each model represent those that might be typically generated. To a reasonable approximation, the results of the simulation can be scaled by the applied voltage to estimate other possibilities. The currents and voltages through and across each of the three diodes and the two capacitors in the aperture-generating oxide were simulated connecting the SPICE model of the ESD source to the SPICE model of the VCSEL. The results for the current through the rightmost diode and for the voltage across the leftmost oxide capacitor are plotted in Figure 6. The mgnitudes of the currents and voltages in the CDM are substantially greater than either of the others, despite the fact that this model had by far the lowest applied voltage. The HBM deposits the greatest energy, however, spreading it over a much longer time. These differences manifest in different damage types and different damage locations.

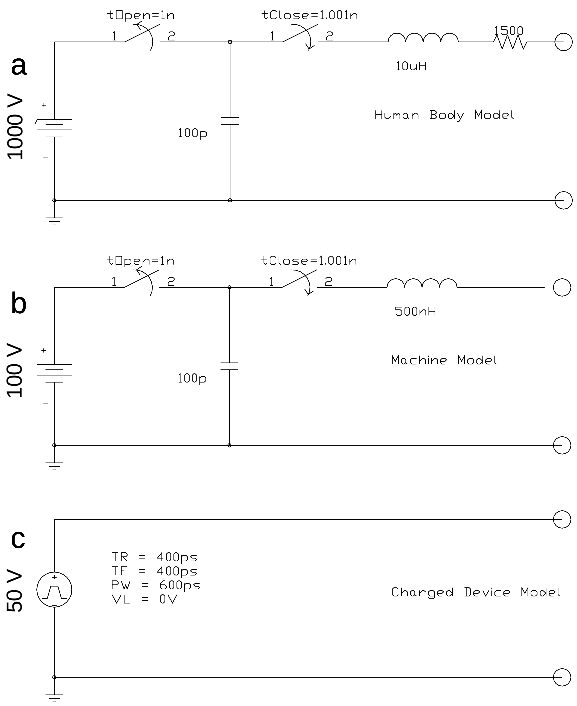

Figure 5. SPICE models employed to simulate HBM (a), MM (b), and CDM (c) ESD events

Figure 7 includes TEM images of VCSELs degraded by various sorts of ESD events. Both plan and cross-sectional views are shown, though due to preparation difficulties they are usually not the same parts in both views. As expected, EOS events, with high currents for times long compared to the VCSEL thermal time constant, cause their greatest damage in the center of the aperture, where symmetry guarantees the highest temperatures will be reached. Damage is spread over a wide area, and often includes clear signs of melting and re-freezing.

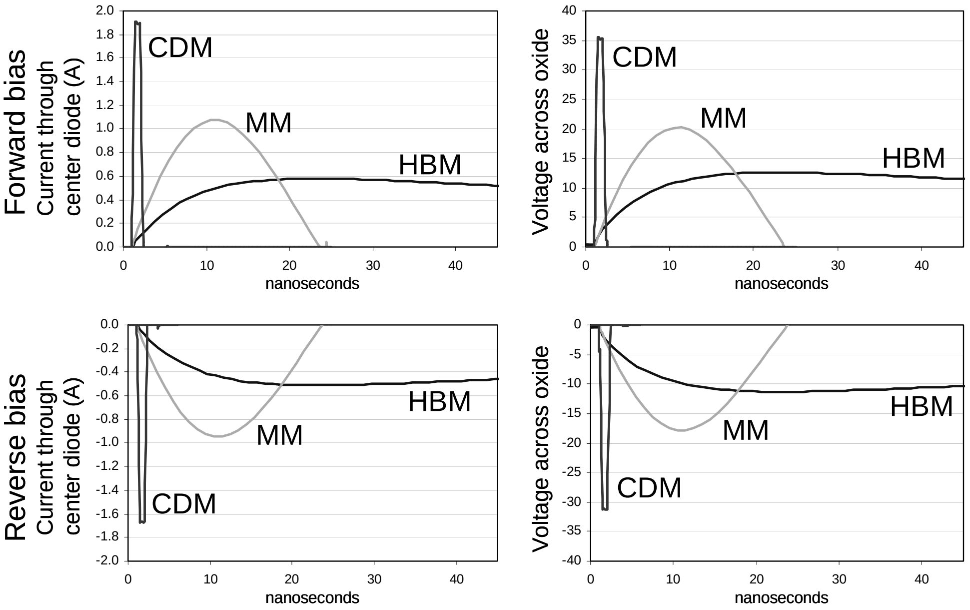

Figure 6. Current through central diode and voltage across oxide capacitor resulting from forward and reverse bias direction ESD “zaps” of three different types. Model voltages were: HBM ±1000 V; MM ±100 V, CDM, ±50 V.

HBM events have a duration approximately 10% of the thermal time constant for the VCSEL as a whole. As a result, substantially higher currents are required for damage, and that damage tends to be localized near the inner edge of the oxide aperture. Because power dissipation is greater in the reverse bias direction, and because that power dissipation is more localized to the junction plane, damage thresholds are lower than in the forward direction. In AOC VCSELs, reverse bias HBM damage almost always occurs first in the plane of the junction, but forward bias damage typically originates in the region of high current density and high mechanical stress in the oxide plane and near the aperture tip.

MM damage usually occurs immediately adjacent to the oxide aperture boundary, or even somewhat beyond, in the region that, for a slower pulse, would be insulated by the oxide.

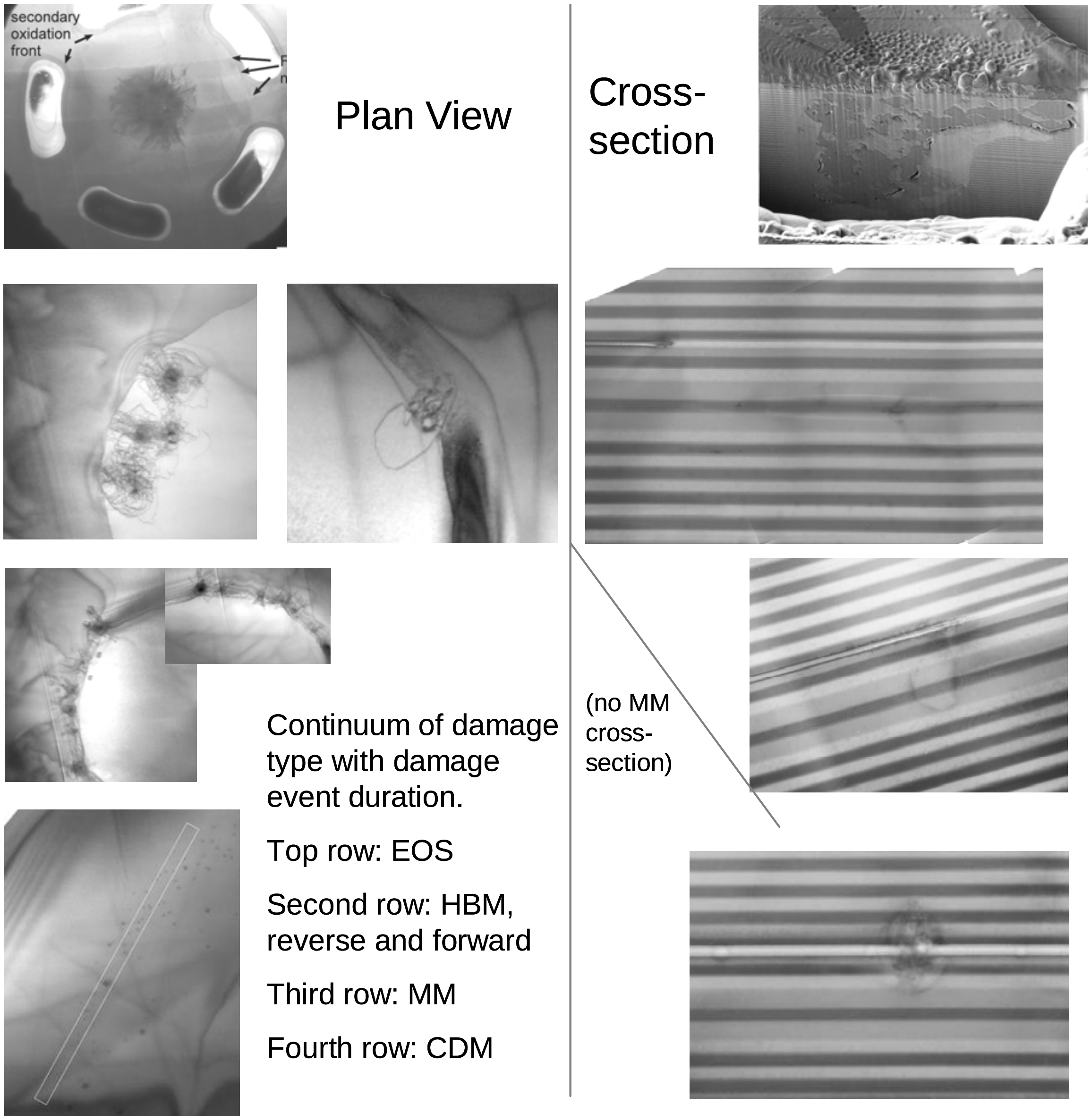

Figure 7. Plan and cross-sectional views of oxide VCSELs damaged by various sorts of ESD events. Vertical and horizontal damage locations differ in predictable ways as damaging pulse edge speed and duration vary. In every case except the CDM damage of the bottom row images, the lateral location of the damage is interior to the oxide aperture; the CDM damage shown here is entirely outside the oxide aperture.

Finally, in the bottommost row of Figure 7, we see the consequences of CDM events. Because they allow almost the entire source voltage to be expressed across the oxide, CDM pulses cause dielectric breakdown. (By analogy to sapphire, which has dielectric breakdown strength of approximately 40 V/µm, dielectric breakdown of typical oxide layers could occur at only a few volts.) In this type of ESD damage, the locus is invariably in the oxide layer itself. Whether it subsequently causes VCSEL failure depends on whether the damage is severe enough to reach the active region.

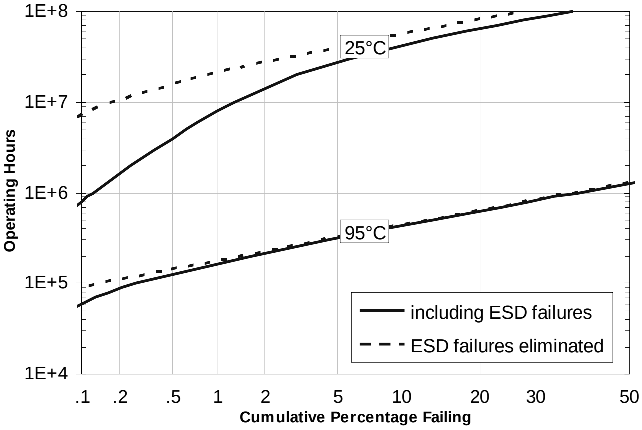

Figure 8. Reliability at two stress levels, with typical ESD statistics and in an ESD-free population.

The wide variety of ESD damage events and sources, and the difficulty in unambiguously detecting the resulting damage in VCSELs, have sometimes led to both skepticism and complacency. For AOC, at least, there is now ample evidence that, after high temperature operation for long times, ESD is the number one killer of VCSELs. This is true even with the wide variety of control measures and electrical screening procedures we and our customers employ. And, of course, new applications tend toward even smaller apertures and thus even greater ESD sensitivity, making elimination of ESD damage ever more difficult. If it can be done, however, substantial reliability improvements are possible. Figure 8 shows the reliability of the AOC 4G oxide VCSEL. The solid curve includes the field failure fraction that was confirmed due to ESD. The dotted curve shows the reliability of the same population if the ESD-damaged parts are not present. There is an order of magnitude improvement at the time that 0.1% of the population has failed (1000 ppm), and substantially greater improvement in the time to, say, 100 ppm failures.

As we learn more about the failure phenomenology and physics of different ESD events, we also inevitably discover new modes of exposure at all levels of assembly, whether component, subassembly, or even in the final circuit (yes, it does happen). Sometimes procedures long assumed safe are revealed to produce rare—or even frequent—damage events. Each newly identified exposure source must be ruthlessly expunged.

5. HIGHER-SPEED SERIAL DATACOMMUNICATIONS DEVELOPMENTS: CHALLENGES OF 4, 8, AND 10 GBPS

5.1 Reliability Considerations

The introduction of optical transceivers at 4 Gbps was supposed by some to be a “freebie” hanging on the coat tails of 2 Gbps VCSELs. In many ways that was true, but in others it was not. At 2 Gbps, the speed of the VCSEL (in particular the ROF [relaxation oscillation frequency]) was generally not an issue, and the packaging was quite easy to manage as well. However, at 4 Gbps, both the packaging parasitics and the intrinsic VCSEL speed are significant contributors to the overall performance of the transmitter functionality. Now, more than ever before, transmitter performance must be interpreted to include both the quality of the optical eye diagram and the reliability of the VCSEL. It is well known that there is a tradeoff between laser reliability and laser speed. The ROF, ν_R is related to the operating current, I, and the threshold current, I_{TH} by

$$\nu_R \propto \frac{1}{2\pi}\sqrt{\frac{1}{t_C \tau_2}\left(\frac{I}{I_{TH}}-1\right)}$$

where t_C is the average photon lifetime in the optical cavity, and τ_2 is the spontaneous emission lifetime. Therefore, for any particular laser, it is advantages to run at the highest current possible. However the reliability acceleration factor, AF, for typical VCSELs scales with I as

$$AF \equiv \frac{TTF_1}{TTF_2} = \left(\frac{I_1}{I_2}\right)^2 \exp\left[\frac{E_A}{k_B}\left(\frac{1}{T_{J2}} - \frac{1}{T_{J1}}\right)\right]$$

Where TTF_X denotes the time to failure at condition x, I_X is the current at condition x, T_{JX} is the VCSEL junction temperature at condition x, E_A is the activation energy of the failure mode, and k_B is Boltzman's constant. These are the fairly standard considerations for long term degradation.[4] However, at 10 Gbps operation, it is also necessary to consider the *type* of aging degradation in the VCSEL. Previous reliability testing of VCSELs for changes in modulation performance found that there was little change in the VCSEL characteristics.[8] Failure mechanisms that lead to changes in the ac performance, in particular those leading to self-pulsation were not observed. However, self-pulsation is not the only thing that can affect long term modulation performance.

The specific way in which the power degrades can also affect modulation performance. For example, most reliability studies are driven by a change in either optical power for a constant current burn in (ACC), or by a change in operating current in a constant power burn in (APC). For practical reasons, all of the burn in data to date at AOC has been collected in constant current mode. (It can be argued that for very reliable devices APC burn-in testing is not possible, since at the extreme temperatures necessary to generate failures, the devices' APC loops no longer perform properly.) For ac performance, it is really necessarily to know the way in which both threshold and slope efficiency of the laser age to affect the total laser power. Understanding of the laser degradation mechanism and the control circuit operation are important for optimizing the long term health of an optical link. Figure 9(a) shows the effects of degradation in slope efficiency and figure 9(b) shows the effects of threshold degradation on operating points for both ACC and APC control circuits. Consider Table 1 below where the effects of aging and laser control circuits are categorized. For the ACC case, both the bias and modulation currents are held constant. For the APC case, only the modulation is constant. It is important to choose the desired control mechanism for the laser aging expected. Since changes in the threshold current can have more than just power budget effects on the link, it is also instructive to look at the change in relative speed of the laser as a function of the change in threshold current. In Figure 10(a) is a plot of ν_R of a laser source biased at constant current at various multiples of threshold, and for a laser biased at constant power. Figure 10(b) is a plot of the relationship between power degradation and threshold degradation, assuming no changes in the slope efficiency.

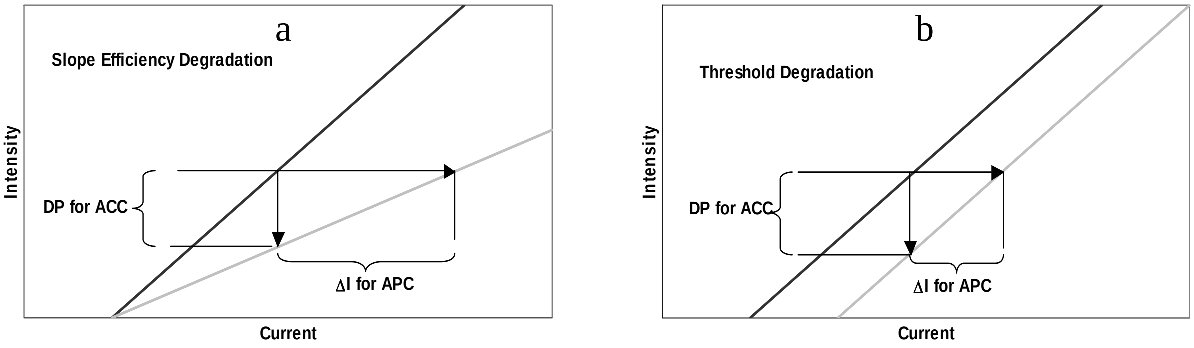

Figure 9. Depiction of the effects of slope efficiency (a) and threshold degradation (b) on the operating point for both ACC and APC control circuits.

Circuit Type	Parameter	Effect of $\Delta\eta$	Effect of ΔI_{TH}
ACC	P_{AVE}	↓	↓
	OMA	↓	↓
	ER	–	↑
	ν_R	–	↓
APC	P_{AVE}	–	–
	OMA	↓	–
	ER	↓	–
	ν_R	–	↓

Table 1. Comparison of laser control schemes and the effect of aging shifts on performance.

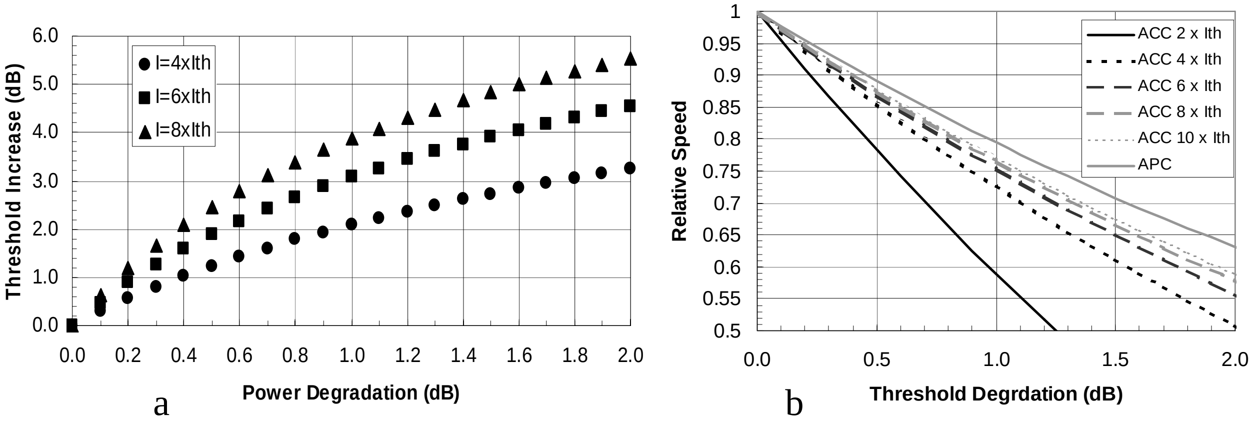

Figure 10. (a) Comparison of laser control schemes and effect of threshold degradation on the ROF, and (b) relationship between threshold change and power change assuming no changes in slope efficiency.

10 Gbps optical data links may be the first application of VCSELs where the effects of long-term aging characteristics have a truly substantial impact on the performance of the system. In particular, the movement in threshold with degradation will affect the overall laser speed, and the movement in slope efficiency (though normally small by comparison) will affect an already very tight optical power budget. Therefore, we believe it may be necessary to recast the time to failure for components used in 10 Gbps data links in terms of time to 1 dB degradation in optical power. Prior reliability modeling and testing at AOC has generally used a 2 dB power degradation criterion. To reset the limits for optical power degradation, the reliability model must be adjusted. For a lognormal distribution, the log of the median lifetime, or μ, must be corrected according to

$$\mu_{new} = \ln\left[\frac{\exp(\mu_{STD})}{AF}\right] - \ln\left[\frac{1-10^{-P_{STD}/10}}{1-10^{-P_{NEW}/10}}\right]$$

where μ_{STD} and P_{STD} are the standard values of the log of the mean time to failure and the power degradation (dB) respectively. μ_{NEW} and P_{NEW} are the calculated changes in the mean lifetime and the new power degradation value. Both the acceleration factor, AF, and the standard deviation of failures, σ, are unchanged. Figure 11 is a plot of the calculated reliability for a 10 Gbps VCSEL using different failure criteria. The change from 2 dB to 1 dB for a failure criterion means that what we will consider to be the wearout lifetime decreases approximately a factor of two. Good thing reliability at a fixed criterion increased more than a factor of two in 2004!

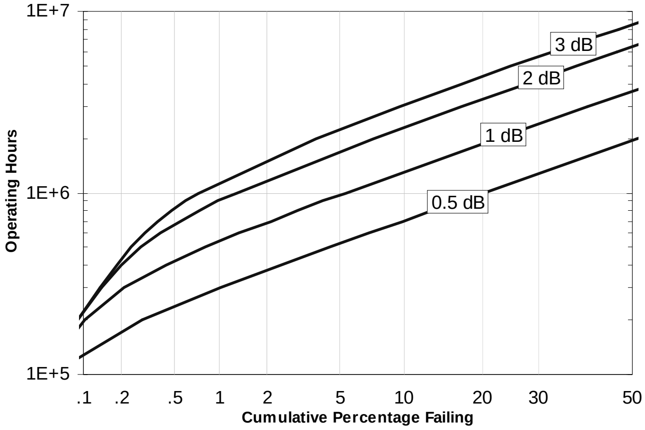

Figure 11. Calculated reliability of 10 Gbps VCSEL at 55°C and 8 mA for various power degradation failure criteria.

From this analysis it would also seem to be more favorable to use an average power control circuit in the application. This is certainly desirable from an ac aging perspective, but care must be taken in the application. Since the VCSEL is operating at very high bias currents, the effects of thermal rollover and reliability must be carefully balanced. To estimate the effects of APC circuits on laser reliability, one must take into account that as the VCSEL degrades in optical power, the control circuit compensates by increasing the bias current, raising the subsequent degradation rate. Whether APC or ACC operation leads to greatest reliability depends on how close the device is operating to the initial threshold current, how close it is operating to the initial rollover current, and the specific reliability metric. Figure 12 is a plot showing the predicted differences in power degradation for 10 Gbps AOC VCSELs in ACC and APC control circuits at two different operating conditions. In this case, APC operation results in a substantially shorter lifetime, though both circuits take more than seventy years to reach even the tightened 1-dB failure criterion.

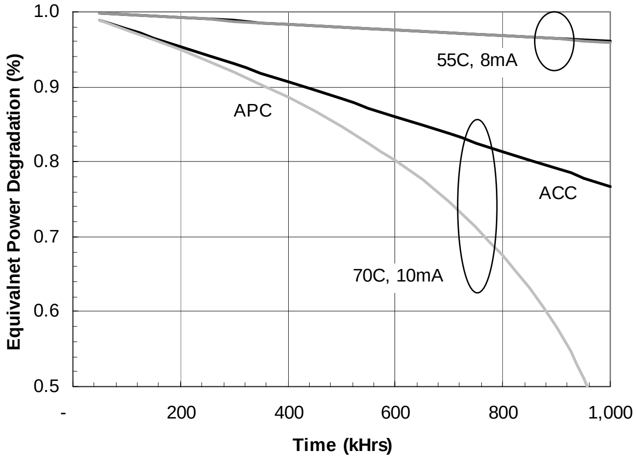

Figure 12. Comparison of reliability for APC (gray) and ACC (black) control circuits at two operating conditions: 55°C, 8mA; and 70°C, 10mA.

5.2 Performance Considerations

While reliability considerations are important to consider in designing 10 Gbps optical data links, they are not the only design constraints. Consider Figure 13 where the worst-case (Class 1 open-bore eye safety, lowest wavelength, maximum spectral width, ER maximum of 6 dB) optical power budget is tabulated. The total optical window is only 2% of the eye safety limit, or roughly 16 µW! Obviously this is an untenable manufacturing situation, and concessions must be made. If the eye safety constraint is relaxed to class 1M, then the window opens to approximately 50 µW, still a very tough manufacturing constraint. Because of the very tight launch budget, laser makers are being forced to significantly tighten limits on the manufacturing process. For example, if the spectral width can be limited to 0.4 nm, then the launch power window increases by roughly 50 µW. Other considerations such as optical coupling efficiency, power tracking, and aging margin are also under heavy specification pressure.

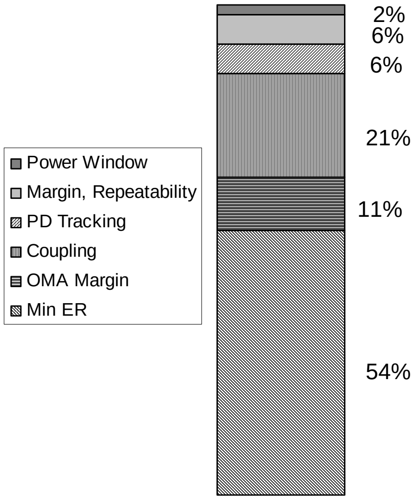

Figure 13. Allocation of 10GB Ethernet power budget for worst case spectral width and wavelength.

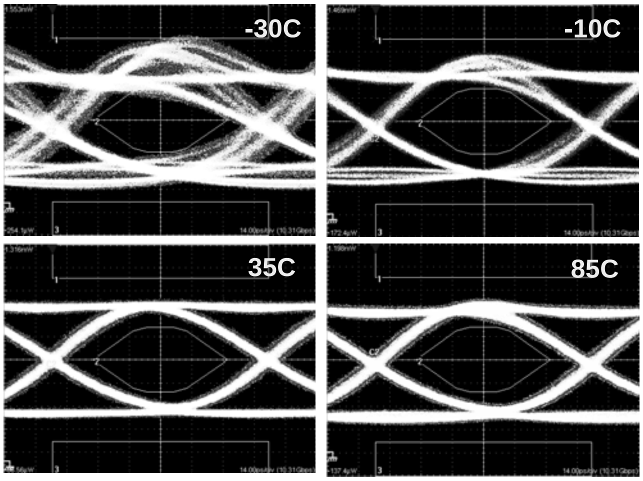

Figure 14. Eye diagrams of a typical 10G VCSEL across temperature at constant AOP and OMA (mask shown with 25% margin).

One of the most difficult issues for 10 Gbps module and VCSEL makers alike is the operation across extended temperature range. Consider the eye diagrams in Figure 14, which are taken across the temperature range of –30 to +85°C. Average power and OMA was maintained across temperature. The eye closure at low temperature is caused by the decrease in the ROF as a function of laser bias. Using pulse mode measurements, the ROF of the VCSEL was measured across temperature and laser current in both the data “ones” and the data “zeroes.” Results are shown in Figure 15. The conclusion is that this VCSEL must be operated at currents in the range of ten times threshold to achieve sufficient eye quality, and that the requirement expressed as the ratio of above-threshold current to threshold current is independent of temperature. As the operating temperature is lowered, the laser efficiency is increased, forcing the laser to operate closer to threshold in an APC circuit, causing the ROF to decrease until it comes in band of the electrical signal. Figure 16 plots the fiber coupled power as a function of $(I-I_{TH})/I_{TH}$, clearly demonstrating the effects of temperature on the effective ROF.

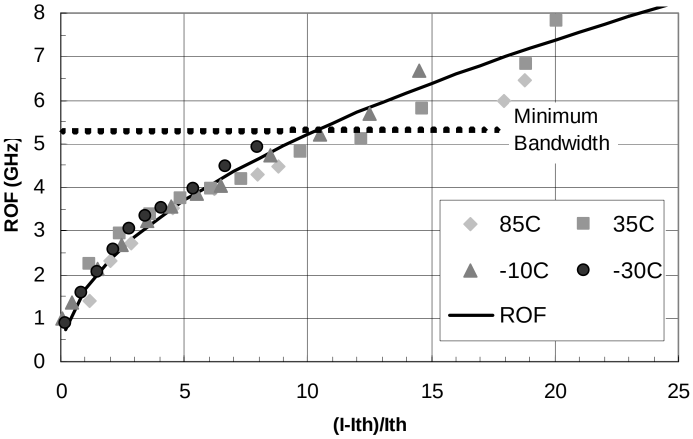

Figure 15. Dependence of ROF as a function of bias and temperature.

While ROF is one effect that can limit operation across temperature, another effect that can exacerbate the overshoot that results from in-band ROF is the effect of modal dynamics on the optical waveforms.[9] Figure 17 shows schematically the variation in gain as a function of temperature. At temperature T_1 the modes to the red side of the cavity have higher gain, which discourages higher order modes of the cavity from lasing. (Recall that in a VCSEL, the higher order modes are blue shifted relative to the fundamental mode, which is the longest supported wavelength.) As the temperature goes to T_2 ($T_2 < T_1$) the available gain for the blue shifted modes increases, allowing for more high order modes (with higher divergence) of the cavity to lase. (The point at which the cavity mode lines up with the gain peak is often referred to as T_0, and is where the minimum threshold current occurs as a function of temperature. Note this is not the same definition of T_0 often used in edge emitting lasers). The higher order modes for the VCSEL cavity do not couple to the optical fiber as well as lower order modes, which leads not only to coupling loss, but also to modal coupling artifacts. Mode dynamics depend on both the current and temperature in the active region, and interact on a time scale of tens to hundreds of picoseconds. The encouragement to lase in higher order modes often leads to overshoot in the VCSEL as the lasing modes move from low divergent, well coupled modes to higher divergent, poorer coupling modes.[9]

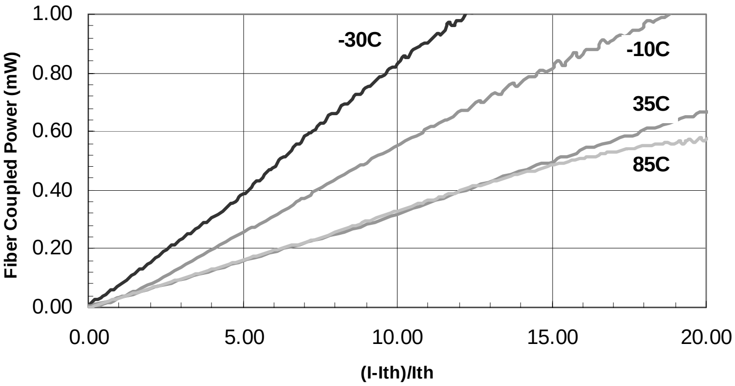

Figure 16. Fiber coupled power as a function of $(I-I_{TH})/I_{TH}$ demonstrating the effects of temperature on threshold multiple at fixed power.

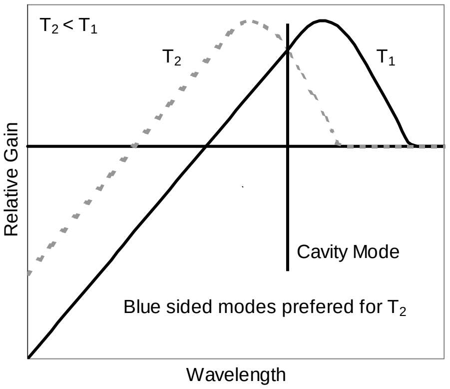

Figure 17. Schematic of gain variation across temperature.

The interacting effects of current and temperature on performance and reliability are of notable importance at 4 Gbps, and are critical at 10 Gbps. It will be interesting in the coming year to see whether market expectations for 8 Gbps VCSEL-based modules to have pricing more similar to lower-speed modules than to 10 Gbps modules can be met with technological solutions. Given that many of today's VCSEL performance and cost characteristics were clearly impossible—so said the experts a few years ago—it could go either way.

6. LONG WAVELENGTH VCSELS

The desire for 1310 nm VCSELs is driven by a need for a lower cost, lower power dissipation, high performance replacement for expensive DFB lasers. At higher data rates FP lasers cannot meet the standards, but DFB lasers remain prohibitively expensive and power hungry making the 1310 nm VCSEL an ideal solution for 4 GB and above medium distance transmission. Especially for emerging high volume applications such as FTTP, it is expected that 1310 nm VCSEL will become lower cost than the FP laser solution and use much less power.

Significant progress in the performance of 1310 nm VCSELs was made during 2004, primarily in reducing intracavity losses. We had significant collaborations with two organizations, Sandia National Labs and Infineon Technologies AG, though the results presented here are only those for epitaxy designed and grown at AOC.[10]

We are still investigating two approaches, all semiconductor mirrors, and bottom semiconductor mirror with top dielectric mirror. To date the best of the all semiconductor mirror devices lase to 145°C, but they do not have the best general emitted power characteristics.

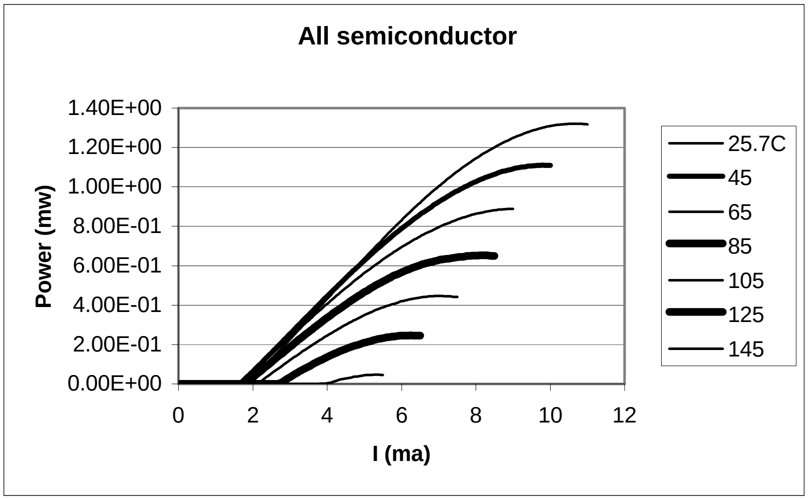

Figure 18. L-I of single mode, all semiconductor mirror ~1300 nm VCSELs showing lasing to 145°C, but relatively small emitted power.

With a dielectric top mirror results at intermediate temperatures, such as 85°C, have been significantly better. Figure 19 shows some results using a dielectric top mirror.

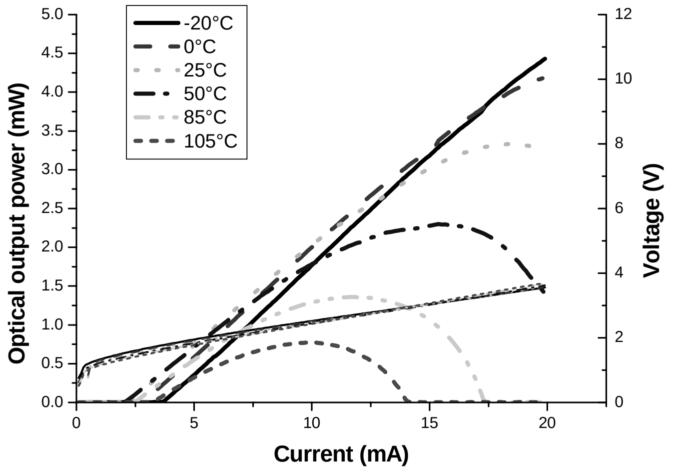

Figure 19, Dielectric top mirror, 1290 nm, single mode to 12 ma, 1.2 mw at 85°C.

Single mode devices have resistance of approximately 80 ohms, and modulation has so far been encouraging with open eyes at 10 GB, and adequate optical isolation reasonably achievable for multimode or single mode fiber, Figure 20.

It is expected that as the processing matures the all semiconductor devices will achieve performance similar to or better than the dielectric mirror case, with all the growth occurring in a single pump down, enhancing manufacturability.

These results are competitive with the best previously reported for VCSELs grown on either GaAs or InP substrates.[11,12]

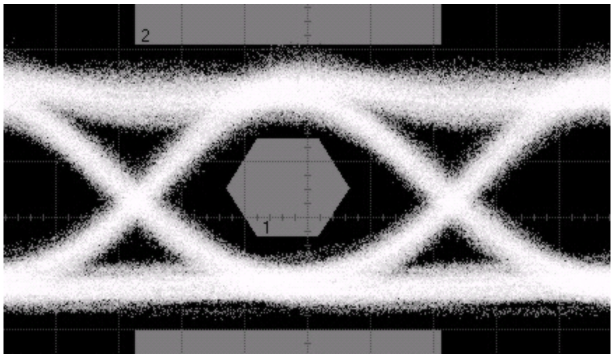

Figure 20. 10 GB Ethernet eye. 1290-nm VCSEL, without isolator.

CONCLUSIONS

As was the case in 2004, we can be certain that 2005 will bring many changes and new challenges to the industry. New data rates—8G seems nearly a lock—will spring to life, new technologies will move from laboratory curiosity to the production floor, and for good or ill many companies existing today will become extinct or be subsumed into other companies. As the VCSEL nears the end of its first decade of commercial life, however, its future continues to look bright. Albeit at a less dizzying rate in adolescence than it had in infancy, VCSELs will expand into new products, and become the technology of choice for new applications. As the wonderful, frustrating secrets of VCSEL operation continue to be revealed, we learn how to make them live even longer, avoid insidious issues like ESD and EOS, and design VCSELs to work more effectively for the unforeseeable applications of the future.

"Become a student of change. It is the only thing that will remain constant" -Anthony D'Angelo

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