High Data Throughput VCSELs

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ABSTRACT

VCSELs continue to be widely deployed in data communication networks. The total bandwidth requirements continue to grow, resulting in higher data rates and utilization of both spatial and wavelength multiplexing. This paper will discuss recent results on VCSELs operating at aggregate speeds up to 1000Gbps as well as the prospects and results on extending to higher serial data rates.

Keywords: VCSEL, vertical cavity laser, reliability, high speed modulation

1. INTRODUCTION

There is a continued interest in increasing the aggregate bandwidth of data communication networks, and as the line rate per channel increases, the need for optical connectivity grows. There are a number of methods to increase optical bandwidth in a given channel besides simply scaling the linline rate. For example, telecommunications equipment manufacturers have long deployed multiple wavelengths in a single optical fiber as a means for increasing throughput. For long haul communications networks this makes perfect economic sense because the vast majority of cost is in placing the fiber cabling in the network. This concept is now beginning to take hold in multimode optical fiber networks with several companies making proposals for coarse wavelength division multiplexing (CWDM) for the data center as a means for increasing the data throughput. But perhaps the most significant increase in connectivity in the data center has been and will continue to be the adoption of parallel optical solutions. The market for parallel optical interconnects is forecasted to grow at more than 50% per year over the next 5 years. Figure 1 is a plot of the total number of parallel optical transceivers actually shipped through 2009 and forecasted through 2014 by LightCounting [1]. Taking the average connection to have 8 VCSELs, this represents more than 20M VCSEL channels in 2014, which will represent more VCSEL channels deployed in parallel than serial interconnects. The primary market drivers will be the adoption into Ethernet applications and InfiniBand server connectivity in high performance computing clusters, with the main product focus being 4 channel and 12 channel devices. The market is also embracing two form factors, the traditional transceiver and the new active optical cable format. Active optical cables (AOCs) embed the optical transceiver within the optical cable and essentially hide it from the user, making connectivity as simple as plugging in an electrical cable. The AOC form factor also has many advantages for the transceiver manufacturer. It removes the often burdensome requirements of optical standards, thereby giving the designer the ability to make different tradeoffs than those required in the various standards. The AOC also offers a significant reduction in the size and weight, and a much more flexible cable than comparable copper interconnect cables. The primary disadvantage cited to AOCs has been that they are not amenable to patch panel architectures. For these applications, transceivers are the preferred embodiment. Still, the number of direct connections and the lower cost structure of the AOCs are driving a transition in the industry to adopt more AOCs. Some market research firms forecast the annual market to be in excess of $1B in several years [2].

Figure 1 Annual parallel transceiver actual (through 2009) and forecasted volume through 2014

Finisar has been developing both optical transceivers and active optical interconnects. The interconnects are marketed under the trade names LaserWire™, QuadWire™, and C.Wire™ for 1, 4, and 12 channels respectively. Figure 2 is a picture of the Finisar’s Active Optical Cable offering.
2. RELIABILITY CONSIDERATIONS

An important consideration for the deployment of parallel optical interconnects is the reliability of the various components and the relevant failure modes [3]. It is critical to understand how the reliability calculations and tests performed on singlet devices [4] can be applied and extended to parallel devices [5]. Reliability of array products is generally estimated by simple exponential statistical extrapolation from reliability of individual components. That is to say if single devices have an estimated reliability of $X_{\text{hrs}}$, then the array reliability is $X_{\text{hrs}}$ divided by the number of elements in the array. This is an overly pessimistic approach for Finisar VCSELs because the reliability statistics are lognormal, and each of the array elements is operating independent of the other devices. For reliability estimates of arrays based on lognormal statistics, instead of dividing the time to failure by the number of units, one multiplies the failure rate by the number of units. This leads to nearly an order of magnitude improvement in predicted array reliability at a given time. Figure 3 describes the estimated reliability of a single element operating at 7mA average current and 55°C ambient, and how it should be properly scaled to array reliability. In this example, the solid line is the predicted time to failure as a function of the percentage of parts failing. For a singlet, the time to 10% failure is shown as the star, and is 3.8M hours. If the reliability is simply scaled by dividing by the number of elements in the array (in this case 10), one would estimate the time to 10% array failures as 0.38M hours, depicted as the triangle in Figure 3. However, when properly scaled, the actual array reliability is shown as the circle in Figure 3, and is 1.6M hours, a factor of 4 more than the simple division, and about 40% of the singlet reliability.

Perhaps an even more important consideration for VCSEL reliability in array applications is infant mortality. For Finisar VCSELs, all devices are burned in at the wafer level using a proprietary technique that has been previously described [4, 5]. A methodology for applying the wafer level burn in technique has recently been developed for VCSELs having both anode and cathode contacts on the top of the device. With the wafer level burn in system, and the reliable by design VCSEL, Finisar continues to experience infant mortality rates less than 10 ppm.

Even with very good reliability for the VCSELs, and a very low infant mortality rate, it is still prudent from a system perspective to incorporate redundancy in the system when possible. The reasoning for this is the cost of failure goes far beyond the cost of the VCSEL itself, or for that matter the entire transceiver. Many of the applications where the interconnects are used are handling critical data, whether in a supercomputer where computational time can be many thousands of dollars per hour, or in a data center where web surfers do not tolerate slow loading applications (e.g. search
engines, social networking, etc). The cost of repairing the system in both down time and man hours is the most significant factor to consider. For this reason, including redundancy in the design is an important consideration to maximize the system up-time. To demonstrate the effect of redundancy on reliability, we need to develop a set of equations. First, let $P_S$ be the probability of a failure of a single element VCSEL; then the probability of an N-element array failure when any single element fails, $P_N$, can be expressed as

$$P_N = 1 - (1 - P_S)^N - NP_S$$

Let the probability of a single element failure when there are R redundant elements (spares) be $P_{R}$, which can be expressed as $P_{R} = P_S^R$, then the probability of an N element array failing when the $R^{th}$ element in the array fails, $P_{NR}$, can be written as:

$$P_{NR} = \prod_{a=0}^{R-1} (N - a)P_S$$

With this formulation, it is only possible to do point estimates for array failures with redundancy. In Table 1 are the calculated time to 1% fails (thousands of hours) for several array sizes and redundancy levels at two common operating conditions. The rows are the number of redundant elements (R=0 means the array fails with the first failure, R=1 means the array fails when the second element fails and so forth).

<table>
<thead>
<tr>
<th>R</th>
<th>N</th>
<th>55C, 8mA Operating Condition</th>
<th>70C, 9mA Operating Condition</th>
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</thead>
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<tr>
<td></td>
<td>1</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
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<td>1280</td>
<td>546</td>
<td>467</td>
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<tr>
<td>3</td>
<td>1500</td>
<td>1170</td>
<td>668</td>
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</tbody>
</table>

Table 1 Calculated time (in thousands of hours) to 1% failure for array sizes of 1, 12, 24, and 168 elements for several redundancy values and operating conditions.

3. **HIGHER SPEED VCSELS**

While deployment of optical interconnects at 10Gbps has begun in earnest, and will be the dominant volume component over the next several years, systems architects are already planning the next generation connections at 25Gbps per channel. This is a result of the confluence of networking standards around this data rate, including Fibre Channel, Ethernet, and InfiniBand. The primary connectivity will likely be InfiniBand in active cables. However at the 25Gbps data rate, connectivity within a box, or even within a board, becomes very attractive. To that end Finisar continues to build on the results published in 2008 [6] where a 30Gbps directly modulated VCSEL was first reported. That device was grown using MBE, and had 3dB optical bandwidth of 17GHz at 25C and open optical eye diagrams and error free optical links at 30Gbps. Here we report on an MOCVD grown VCSEL with similar bandwidth. The measured optical bandwidth ($|S_{21}|$) characteristic as a function of current and temperature is shown in Figure 4. This VCSEL will be further described in upcoming publications.
4. ALTERNATE WAVELENGTH VCSELS

In some applications it is desirable to use installed multimode fiber, which in nearly all cases today is single strand and not ribbon cable. For these cases, the choice of a wavelength division multiplexed solution would be beneficial. Finisar has developed VCSELs operating on a CWDM grid from 775nm to 980nm. Speeds up to 5Gbps are readily available as standard products.

For extremely high data communications throughput, Finisar has also developed a two dimensional 12x14 array of bottom-emitting VCSELs operating at 1000nm that is compatible with flip chip packaging. We chose operation at 1000nm for several reasons; (a) the well known improvement in high speed operation resulting from the increase in differential gain from strained InGaAs quantum wells, (b) transparency of the GaAs substrates used to fabricate the VCSELs and the InP substrates used to fabricate the companion photodiodes, (c) minimization of the absorption in the polymers used to fabricate optical circuit boards, (d) compatibility with the installed multi-mode optical fiber which should maintain reasonable bandwidth at 1000nm which is between the first and second operating windows. Figure 5A is a plot of the light output and forward voltage as a function of current for 25 and 85C operation. Even at 85C, the threshold current is less than 1mA. Figure 5B is the measured optical spectrum of the bottom emitting VCSEL at currents from 2 to 10mA and at temperatures of 25C (left hand side) and 85C (right hand side). The RMS spectral width is less than 0.5nm for all operating conditions. Unfiltered optical eye diagrams measured at 8.5Gbps and 9mA at 25C and 85C are shown in Figure 6A and 6B respectively. A top view of a section of the array is shown in Figure 6C. Each element is capable of operating in excess of 8.5Gbps for aggregate data throughput of 1.5Tbps. Figure 7 is a typical plot of the threshold current, slope efficiency, optical power at 6mA, and forward voltage for each of the elements in the two-dimensional array measured on wafer at 80C ambient temperature and after the Stabilaze® wafer level burn in process.

Figure 5 Light output and forward voltage as a function of current for temperatures of 25 and 85C. (B) Optical spectrum at temperatures of 25C and 85C for several bias currents.

Figure 6 Optical eye diagram at (A) 25C and (B) 95C. (C) Photograph of a portion of the 2D VCSEL array.
5. CONCLUSION

In this paper we have presented results on VCSELs for applications in high speed interconnects ranging from single channel to 168 channel VCSELs and speeds up to 25Gbps. VCSELs will continue to play an ever increasing role in the future of high speed interconnections as the physical limitations of copper solutions become more daunting to handle at the system level.

6. ACKNOWLEDGEMENTS

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REFERENCES

[1] LightCounting market forecast 2009


[7] Laserwire™, QuadWire™, C.Wire™ and Stabilaze® are trademarks of the Finisar Corporation.