APPLICATION NOTES

Optical Modes In VCSELs

LONGITUDINAL LASER MODES

Vertical Cavity Surface Emitting Lasers (VCSELs) are single-longitudinal mode (SLM) lasers. This is because of the extremely short optical cavity in the direction of oscillation.

Consider the typical VCSEL structure in Figure 1. In this example, the gain region consists of three quantum wells placed in a one-wavelength thick spacer region. On either side of the spacer region, there are extremely high reflectivity mirrors made from semiconductors that have total reflectivity greater than 99.5%. The mirrors are fabricated from altering material layers that are $\lambda/4$ thick to form a Distributed Bragg Reflector (DBR). Superimposed on the structure is a schematic of the electric field in the VCSEL.

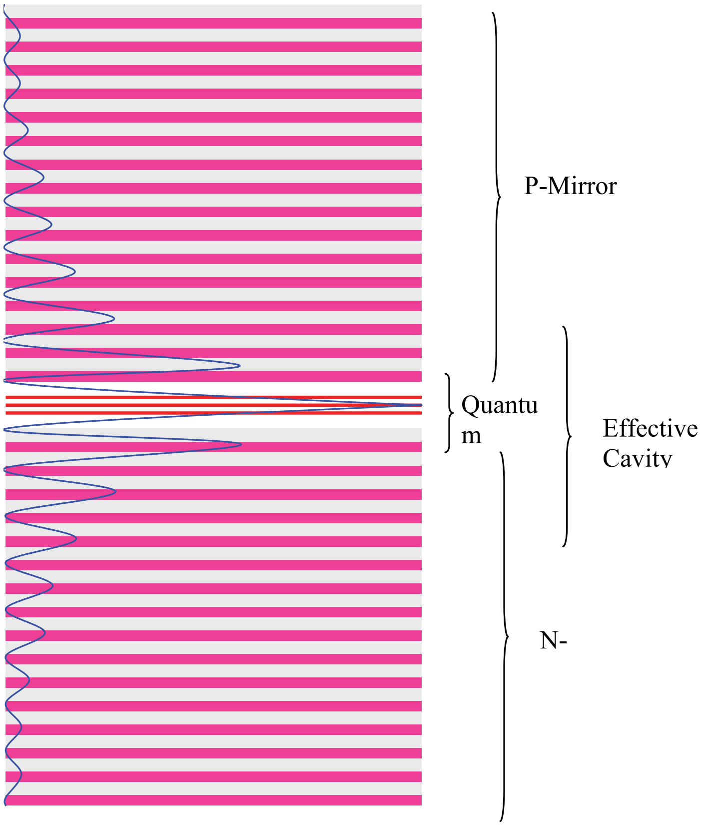

Figure 1 Schematic view of VCSEL and Electric Field

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The total cavity length of the VCSEL, L_{EFF}, is expressed as the sum of the active region thickness plus the so-called penetration depth of the electric field into the DBR structure. Finally, the longitudinal mode spacing of VCSEL can be expressed as

$$\Delta\lambda = \frac{\lambda^2}{2n_{EFF}L_{EFF}}$$

where nEFF is the average index of refraction of the mirrors. Note that the exact penetration depth, which may be different for the N and P mirrors can be found from the mirror properties. Typical longitudinal mode spacing of a VCSEL is 30nm, while the longitudinal mode spacing of a typical cleaved cavity edge-emitting laser (EEL) may be only 0.3nm. Now, when the gain profile of the active region is taken into account, and the stop band of the DBR is also considered, it is easy to see why a VCSEL will only lase in a single longitudinal mode. This is shown in the schematically in Figure 2. One can see from this picture that the longitudinal mode spacing of the VCSEL is approximately the same width as the stop band of the DBR, and are significantly removed from the center of the cavity. (The dip in the DBR spectrum is the Fabry-Perot resonance of the entire VCSEL structure and is measured by white light reflectance of the entire structure.) In addition, there is negative gain for the other cavity modes. In contrast, the longitudinal mode spacing of an EEL can be very small, and there is essentially very little difference in cavity reflectance and gain among the several center modes. A type of EEL can be made to emit in a single wavelength by utilizing distributed feedback (DFB) to the laser cavity. This is typically done by using lithography to define a grating structure in the laser to provide wavelength selective feedback.

TRANSVERSE LASER MODES

Most communications grade FPs and DFBs are made to be single transverse mode by defining a ridge waveguide structure to limit the lateral extent of the electric field. Sometimes it is advantageous to allow more than one transverse laser mode to exist in an EEL, especially when high power operation is desired. The vertical extent of the field is generally defined by a refractive index guiding structure in the epitaxial growth. One such structure is the commonly used Graded Index Separate Confinement Heterostructure (GRINSCH) laser. In a VCSEL, the transverse laser modes are controlled by several parameters, including the lateral oxidation or proton implantation used to steer current into the active region, the self heating of the active region, and particular design of the oxidation boundary.

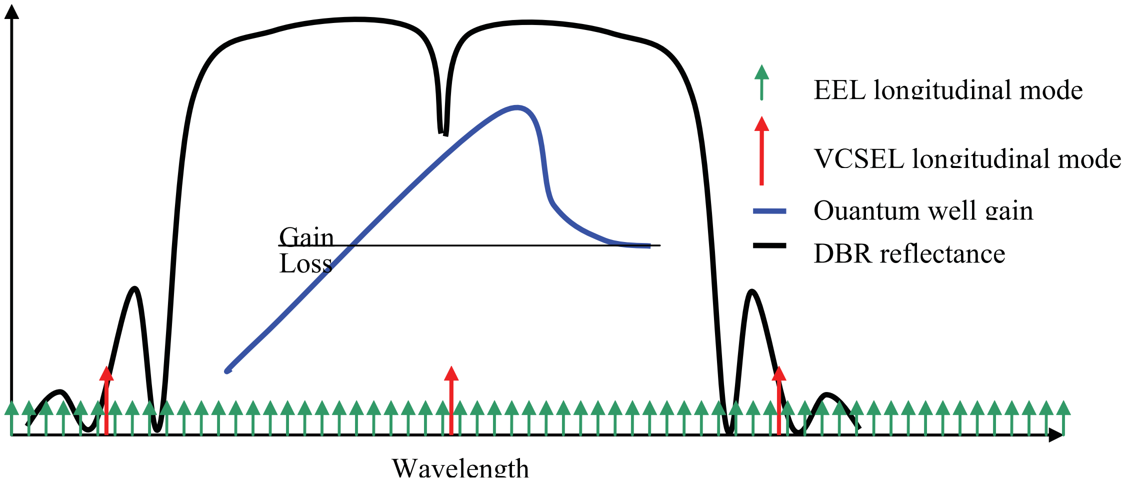

Figure 2 Schematic of DBR reflectance (observed from the top of the VCSEL), mode spacing and quantum well gain curve. The mode spacing of the EEL is not to scale, and is much finer than depicted here.

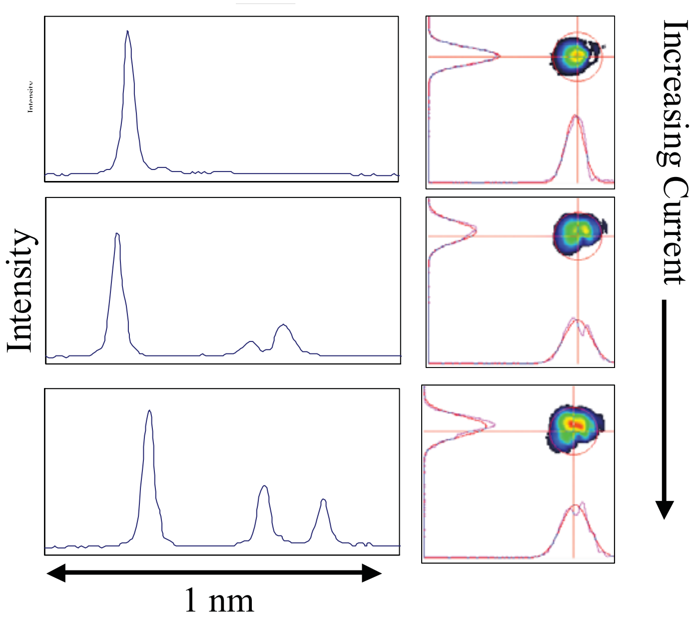

Figure 3 Optical spectrum (linear scale) and corresponding near field image of a typical proton isolated VCSEL

PROTON IMPLANTED (PI) VCSELS

The first VCSELs used in production were fabricated using proton implantation to guide the current into the active region. The proton implantation process provides very little to no change in the optical properties of the semiconductor material, and therefore has very little effect on the mode forming dynamics of the VCSEL. Most PI VCSELs have active area diameters that are quite large in extent relative to the mode field diameters supported by the vertical structure. The modes of a PI VCSEL are generally treated as gain guided, and tend to appear in spots where the gain and/or loss is locally different than surrounding material. The spot size of the mode tends to be on the order of 3-5um.

At threshold, there is typically only one mode lasing, and as the current increases, lasing occurs in other regions of the active area. Each mode is characterized by a unique wavelength, and is polarized with respect to the crystallographic axes. This is shown Figure 3, where both near field images of the VCSEL active region and optical spectra are recorded as the current is increased above threshold. The changes in the optical spectrum are also presented as a function of both current and temperature in Figure 4.

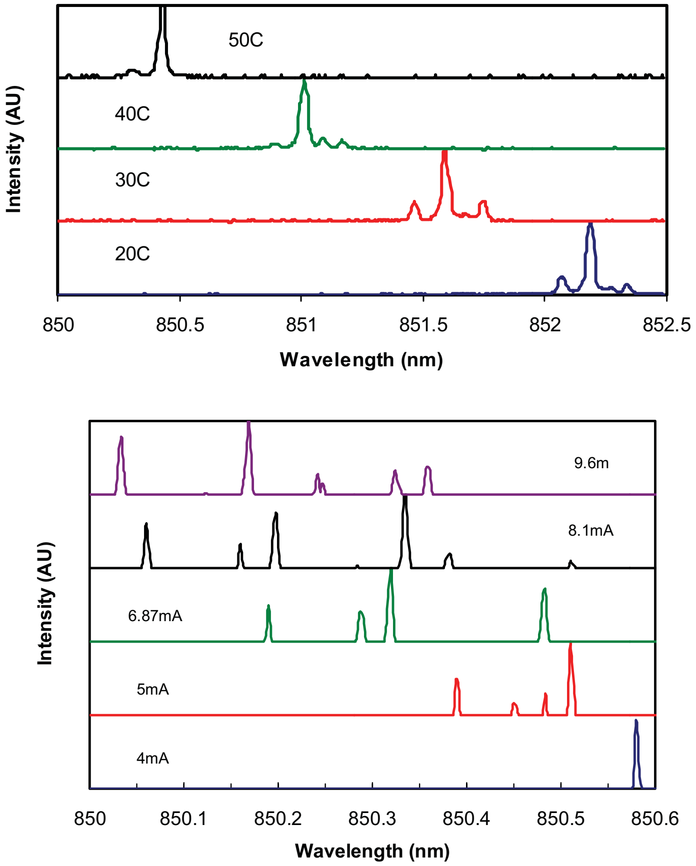

Figure 4 Typical optical spectrum (linear scale) of a PI VCSEL as a function of temperature and bias current. Typical tuning characteristics ar 0.06nm/C, and 0.03nm/mA

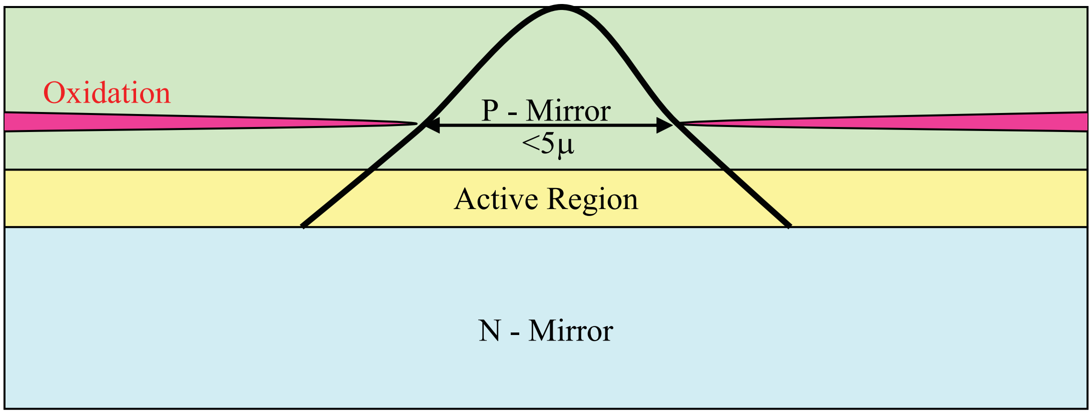

Figure 5 Schematic cross section of a SM VCSEL

SINGLE MODE (SM) VCSELS

The easiest VCSEL to conceptualize is a single transverse mode (STM) VCSEL. An STM VCSEL is fabricated by reducing the lateral extent of the fundamental optical mode such that it is the only allowable mode of the cavity. Typically this is done using a lateral oxidation layer to form an aperture less than 5um in extent. This is shown schematically in Figure 6. Most VCSELs do not have a method to control the polarization of the optical mode, which may allow for coexistence of two or more polarization modes. The polarizations are slightly different in wavelength, typically less than 0.1 Angstroms or less. A typical optical spectrum of a single mode VCSEL is shown in Figure 7. Please note that the optical linewidth of a single mode laser cannot be measured on a typical optical spectrum analyzer. Accurate measurements of the optical linewidth must be done with a Fabry-Perot interferometer or other means. The typical optical linewidth of AOC single mode lasers is less than 100MHz.

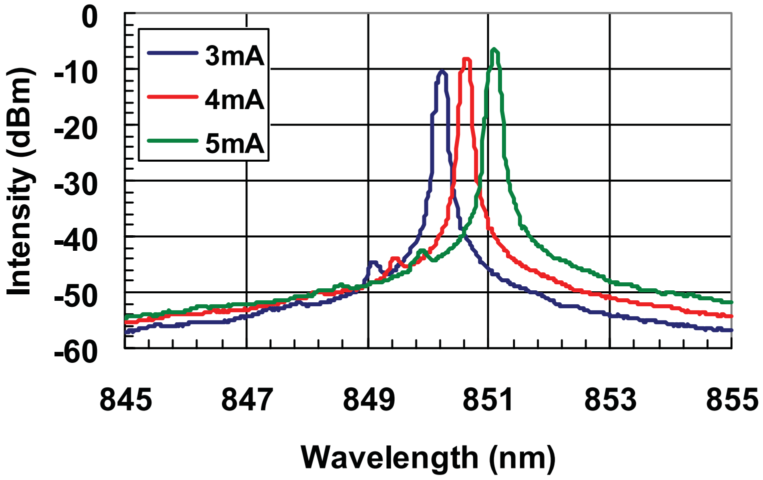

Figure 6 Typical optical spectrum of a Single mode VCSEL as a function of current

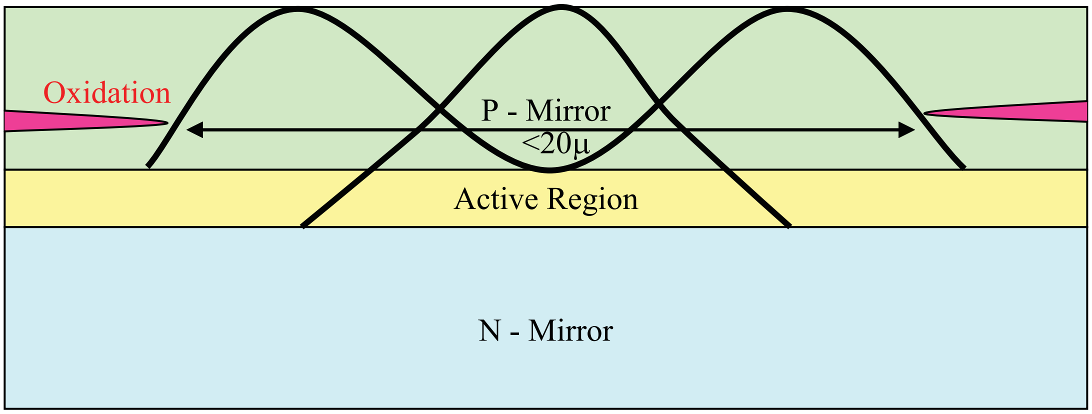

Figure 7 Cross section schematic of a multitransverse mode VCSEL

MULTITRANSVERSE MODE (MTM) OXIDE VCSELS

MTM oxide VCSELs are the workhorse in data communications. They are most utilized because they offer modulation improvements over a proton VCSEL, and reliability improvement over a single mode VCSEL. They can be made to be compatible with drive electronics and inexpensive optical coupling. A MTM oxide VCSEL allows more than one optical mode inside the laser cavity. The addition of the oxidation boundary introduces a significant optical effect into the VCSEL cavity. As a result, modes are often more predictable. Higher order modes are often modeled as Laguerre-Gaussian shape or Bessel function in shape. The exact definition of the mode shape is a difficult numerical calculation, and is highly dependent on a number of design parameters. In this note, we will simply demonstrate some of the possible higher order modes in a VCSEL. Figure 7 is a schematic of the cross section of a multimode VCSEL. Figure 8 shows the near field profiles of both proton and oxide aperture VCSELs. Figure 9 shows the optical spectrum as a function of current for a typical 10G VCSEL.

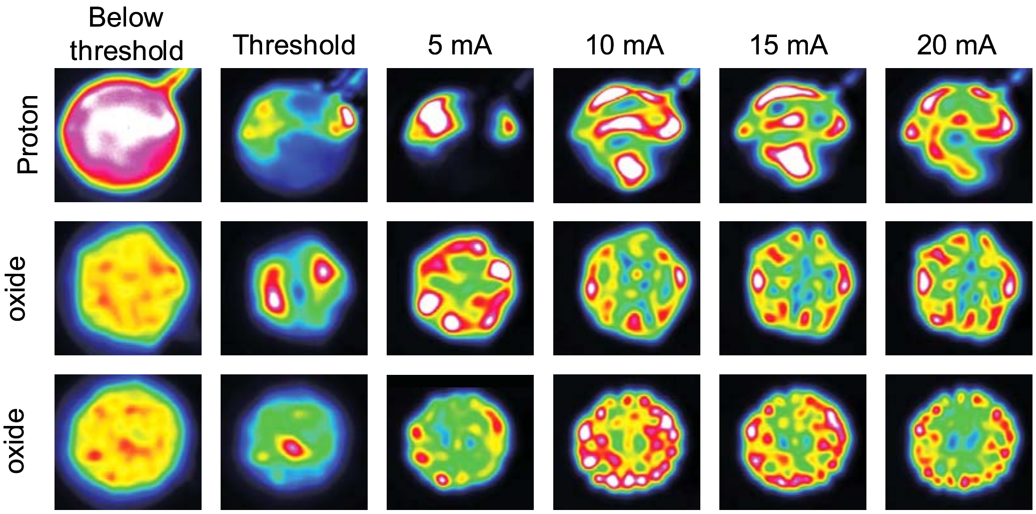

Figure 8 Near field images of a Proton and 2 different oxide VCSELs

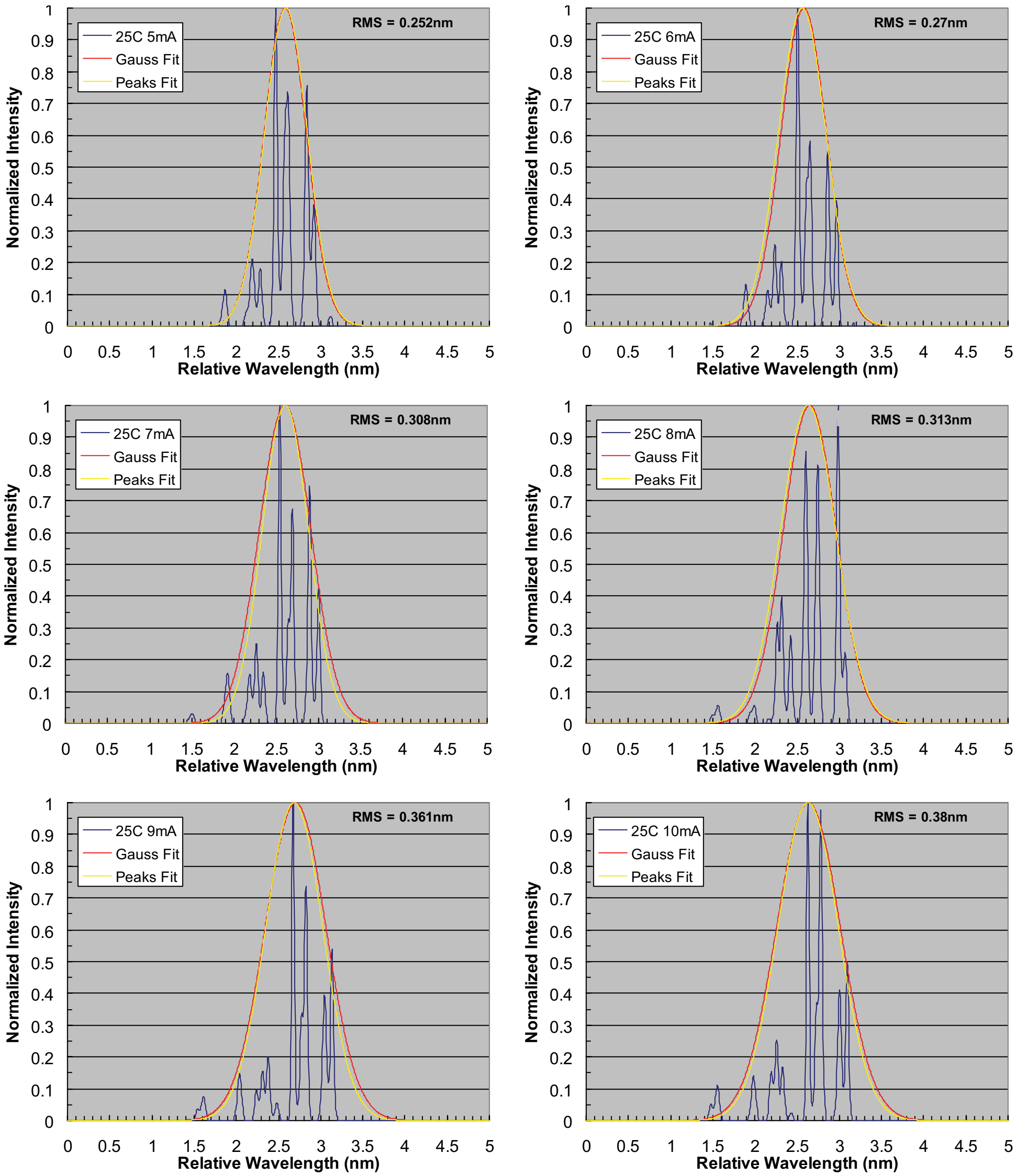

Figure 9 Measured Optical Spectrum of a typical 10Gbps VCSEL as a function of current measured at room temperature.
The RMS Spectral width changes at roughly 0.03nm/mA

When measuring the spectral width of a VCSEL, it is important to understand the definition of the measurement. Some measurements of spectral width are not suitable for use in VCSELs. When measuring single mode devices, the linewidth can be quite narrow, a MHz, thus techniques consitent with DFB lasers must be utilized. When measuring the spectral width of a MTM VCSEL, it is most useful to consider the technique put forward in the recent revisions to the commonly used FOTP-127. Here, the VCSEL modes are carefully measured and resolved, and a guassian approximation is utilized to calculate the RMS spectral width. This is the value typically used in various fiber optic link budget analyses (though this is a very pessimistic approach).

POLARIZATION IN VCSELS

AOC VCSELs are not designed to emit in a single polarization state. At threshold, all VCSELs will generally lase in a single polarization angle. However, as more modes appear, there is no control on the polarization. Typically, the polarization is along the two orthogonal cleavage planes of the GaAs substrtate. In a typical VCSEL operating above threshold, both polarization states are present. Since the polarization is not controlled, it can also randomly switch during normal operation, and even from pulse to pulse. It is therefore critical that there be no polarization selective optics in the VCSEL beam path. Finally, these polarization flips do not present problems with operation on multimode fiber optics as the polarization dispersion is neglible for the short distances spans typically deployed.

MODAL EFFECTS ON VCSEL EYE QUALITY

The optical energy in a VCSEL can move from mode to mode, and switch polarization during an optical pulse, or even randomly in time and temperature. Significant mode competition effects can also be observed in VCSELs as the device is coming to equilibrium. A model was previously developed that demonstrated excellent agreement between theoretical calculations and measured results [1]. The most important conclusion reached in that modeling exercise was that there can be significant pulse shape distortion caused by modal selective coupling in a VCSEL. However, if all of the VCSEL modes are equally coupled, then there is no degradation in the optical performance of the VCSEL due to mode competition. Figure 10 contains three pictures which are repeated below from this paper for clarity.

In oxide VCSELs, the effect of mode selective coupling is generally seen as overshoot in the optical signal. This can be readily observed by decoupling a TOSA in the direction of the fiber axis (pulling the connector slightly out of the housing).

EFFECTS OF OPTICAL MODES ON OPTICAL DATA LINKS

The change of wavelength and mode hopping in optical data links is an important factor in single mode fiber data links because of chromatic dispersion. In multimode fiber data links, there is no appreciable chromatic dispersion, and the effect that must be considered is the change in optical bandwidth of the fiber. Other effects such as mode partition noise must also be considered. These are taken together as the "k" factor in common link budget analysis techniques such as those employed in Ethernet analysis [2,3]. Typical values used are k=0.5, and this is very conservative for the link analysis.

CONCLUSIONS

Nearly all VCSELs in use for data communications are multi-transverse mode lasers. There is generally no specific intent to control the mode forming dynamics of the laser, or the polarization of the particular laser modes. Because of this, it is of critical importance to design the optics used in fiber coupling to uniformly and completely sample all of the optical modes. The effects of modal dispersion in an optical fiber are neglible in multimode fibers as a result of spectral changes in the VCSEL. Mode hopping and Mode partitioning in the VCSEL are mitigated using appropriate collection optics. The effects in the fiber are once again minimal.

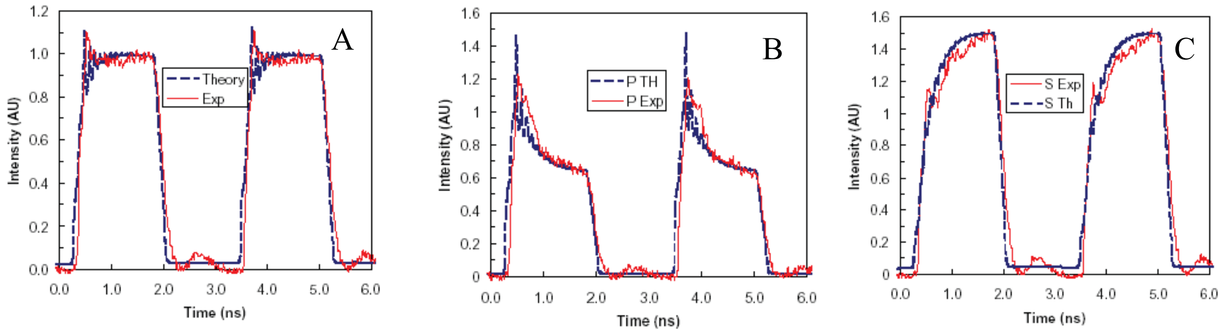

Figure 10 Total emitted power (A), and mode selective coupling (B) and (C) introduced by polarization

REFERENCES

[1] J. Tatum et al, "High Speed Characteristics of VCSELs," Proc. SPIE 3004, 1997. Available at www.finisar.com/aoc.php

[2] P. Pepelugjuski, et al, "Effect of launch conditions on power penalties in Gigabit links using 62.5um core fibers at short wavelength, NIST symposium on fiber modal bandwidth, 1998. Available at www.finisar.com/aoc.php

[3] See for example *Gigabit Ethernetworking,* by Cunningham and Lane, ISBN:1578700620

ADVANCED OPTICAL COMPONENTS

Finisar's ADVANCED OPTICAL COMPONENTS division was formed through strategic acquisition of key optical component suppliers. The company has led the industry in high volume Vertical Cavity Surface Emitting Laser (VCSEL) and associated detector technology since 1996. VCSELs have become the primary laser source for optical data communication, and are rapidly expanding into a wide variety of sensor applications. VCSELs' superior reliability, low drive current, high coupled power, narrow and circularly symmetric beam and versatile packaging options (including arrays) are enabling solutions not possible with other optical technologies. ADVANCED OPTICAL COMPONENTS is also a key supplier of Fabrey-Perot (FP) and Distributed Feedback (DFB) Lasers, and Optical Isolators (OI) for use in single mode fiber data and telecommunications networks

LOCATION

- Allen, TX - Business unit headquarters, VCSEL wafer growth, wafer fabrication and TO package assembly.
- Fremont, CA – Wafer growth and fabrication of 1310 to 1550nm FP and DFB lasers.
- Shanghai, PRC – Optical passives assembly, including optical isolators and splitters.

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- 1, 2, 4, 8, and 10Gbps serial SW DETECTOR solutions
- VCSEL and detector arrays
- 1, 2, 4, 8, and 10Gbps FP and DFB solutions at 1310 and 1550nm
- 1, 2, 4, 8, and 10Gbps serial LW DETECTOR solutions
- Optical Isolators from 1260 to 1600nm range
- Laser packaging in TO46, TO56, and Optical subassemblies with SC, LC, and MU interfaces for communication networks
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