

An Investigation of Mode Partitioning in VCSELS

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**mode partitioning,
VCSEL**

Mode partitioning, quantified in terms of a normalised mode partitioning parameter k , was investigated in laser diodes operating under CW and PRBS modulation @ 1.0625 Gbit/s. A comparison was made between VCSELS and Fabry-Perot edge emitters. Individual laser modes, (or in the case of VCSELS, groups of modes), were preselected using an optical spectrum analyser and monitored using a sensitive APD. By monitoring the statistical distribution of the APD signal, the modal fluctuations were recorded and used to calculate k . The value of k was found to be higher, indicating stronger mode partitioning, when the bias current was closer to threshold for CW operation and when the laser was switched rapidly under modulation.

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Project Dissertation

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Abstract

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Introduction

One of the current projects at Hewlett Packard Laboratories is an investigation into the potential use of multi-transverse-mode Vertical Cavity Surface Emitting Lasers (VCSELs) as transmitters for Gbit/s optical backbone links in local area networks (LANs). The background to this project is outlined below. The problems with optical fibre links are described. These include the effects of modal noise (MN) and mode partitioning noise (MPN). This is followed by an explanation of the expected benefits of using multi-transverse-mode VCSELs, highlighting the importance of mode partitioning in VCSELs. The evolution of the experimental technique throughout the project is presented, along with results gathered at each stage. The main points are then summarised and suggestions for further investigation are made.

The data rates required in LAN optical fibre backbone links is expected to increase to at least 1 Gbit/s in the near future [1]. Efforts are being made to find a cheap alternative to the LED transmitters used at present and to avoid the costly task of replacing installed multimode fibre with single mode fibre. The LEDs must be replaced because they cannot be modulated at the Gbit/s speeds required. However the use of a coherent laser source with multimode fibres leads to problems which can impair the system performance.

Modal Noise

Once light from a coherent laser has travelled through a multimode fibre, a speckle pattern is produced across the fibre output face from interference between guided modes. Any phase or amplitude changes of the modes will affect the coherent superposition formed at each point on the end cross section of the fibre. This change is so sensitive that it can be used for sensing applications [2]. These changes to the speckle pattern may be produced by fibre movement or by changes in the output of the laser itself. Losses at splices, fibre connectors, fibre discontinuities or losses due to a detector with an active area smaller than the illuminating beam cross section, are all spatially selective and therefore dependent on the speckle pattern. Shown below (Fig. 1) is the spatial selection due to a lateral mismatch between two multimode fibres.

The change in spatial distribution of intensity in any of these examples can cause a variation in the received power and hence noise in the system.

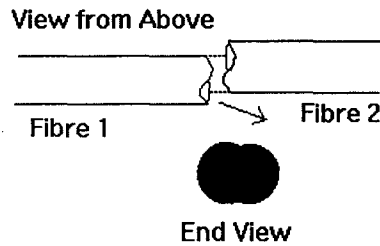


Fig. 1 *Mode selective loss effect of laterally misaligned fibres.*

As the light propagates along the fibre, dispersion causes a delay between different modes which becomes large compared to the coherence time of the source and so the speckle contrast diminishes. After a sufficient length of fibre the speckle pattern homogenises and is said to be “washed out”. All spatially selective losses which are far enough from the source to receive a washed out speckle pattern will not cause modal noise because the power lost will remain a constant fraction of the total and will not be dependent on which modes are present. The problem of modal noise does not arise in single mode fibre because no speckle pattern is possible with only one waveguide mode.

Most edge emitting laser diodes stimulate emission in more than one longitudinal mode, each competing with the others for a share of the gain available. This gain is provided by the carrier population inversion, in the active region of the laser in and near to the depletion layer of the diode. Assuming a reasonably stable temperature, negligible external reflection influences and a short time span compared to the laser lifetime, the relative fluctuation in the total power output of the laser diode biased at a constant level is usually very small. However competition for gain amongst individual modes may result in large relative fluctuations in the proportion of the total power being emitted by a particular mode. As a result, mode fluctuations are strongly anti-correlated, i.e. as some modes gain power others must simultaneously lose power to maintain a constant total laser output. This effect is called mode partitioning.

Mode partitioning produces high frequency changes in the speckle pattern by varying the relative power of modes which interfere to produce it. Therefore modal noise is produced by low speed physical changes in the fibre and high speed changes in the laser source.

Incoherent light from LEDs produced by spontaneous emission is launched into a multimode fibre without any speckle pattern and hence modal noise is eliminated. This advantage and their low cost, are the main reasons for their use, in multimode fibre links.

Mode Partition Noise

Mode partition noise occurs in multimode and single-mode fibres, although in the former, it is usually small in comparison to modal noise.

When different longitudinal modes (Fig. 2) are launched into a single mode fibre, dispersion causes each one to propagate at a different speed. If the laser is also exhibiting strong mode partitioning, then large power fluctuations will occur at the fibre output, due to the simultaneous arrival of different modes each of which may have been launched with an arbitrarily large share of the laser output power. This effect is called mode partition noise. The mode partitioning of the laser can be quantified - with a few simplifying assumptions - using a parameter k first introduced by Ogawa [3].

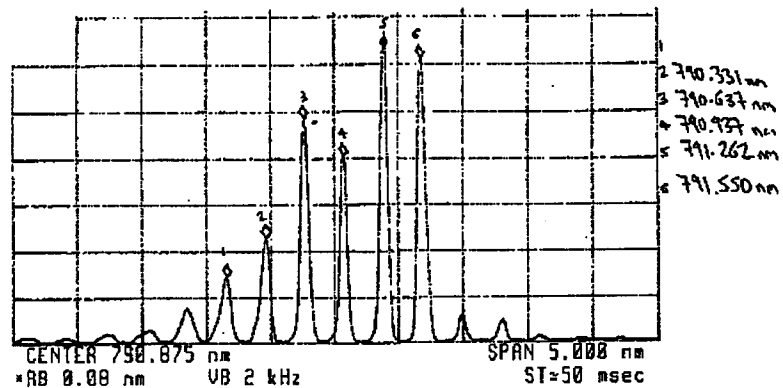


Fig. 2 Longitudinal modes of a CD laser, each with a different wavelength.

To simplify the modelling of mode partitioning, the first thing assumed is that the total output power of the laser is constant. If the laser is modulated, this means a constant total power in the 'on' state from one pulse to the next is taken as a reference. This provides the basis for normalisation of all modal power contributions in terms of the total power, so that the sum of the power in all modes comes to one. The second simplification is to consider only those modes which are lasing. If there are N such modes then these two assumptions can be summarised by equ. 1, where a_i is the power amplitude of the i th mode.

$$\sum_{i=1}^N a_i = 1 \quad (1)$$

Under these conditions, the normalised k of the i th mode is defined by equ. 2,

$$k_i^2 = \frac{\overline{a_i^2} - (\overline{a_i})^2}{\overline{a_i} - (\overline{a_i})^2} \quad (2)$$

and the k of the laser is defined by equ. 3.

$$k_{laser}^2 = \sum_{i=1}^N k_i^2 \quad (3)$$

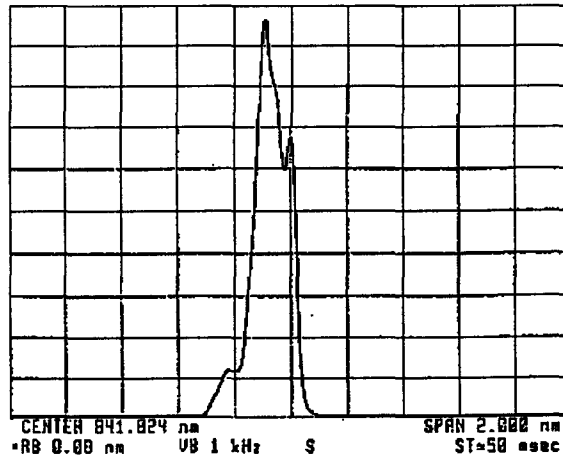


Fig. 3 VCSEL spectrum. Individual modes are not resolved (RES. BW ~0.04 nm)

VCSEL advantages

The large number of transverse modes lasing in a VCSEL reduces the overall laser coherence time [4]. This reduction in coherence time reduces the effects of modal noise by decreasing the length of fibre needed for speckle pattern homogenisation. If the number of longitudinal modes in a Fabry-Perot laser were increased to reduce its coherence, the linewidth of the laser would increase proportionally with the number of modes. This would increase the effect of any fibre dispersion and result in a poor trade-off. With a VCSEL it is possible to increase the number of transverse modes without significantly broadening the spectrum and thus keeping dispersion problems to a minimum.

Given that VCSEL degenerate modes may overlap in wavelength, the number of modes present cannot be inferred directly by examining the laser spectrum (Fig. 3). This means that mode partitioning in a VCSEL, that is power sharing between transverse modes of the laser, does not automatically represent power movement to different wavelengths. This key difference between longitudinal and transverse lasers makes mode partition noise harder to predict for VCSELs if mode partitioning is represented using a k value for each transverse mode.

This strict definition of k was not measured experimentally. Two transverse modes with wavelengths so close together that they cannot be resolved, can transfer power from one to the other without this being recorded. It is only possible, with the techniques used here, to observe mode partitioning if the power transfers across a measurable change in wavelength. The important considerations for modal noise are the changing power levels at different wavelengths and the changing spatial distribution of power in the laser near field, both of which will affect the speckle pattern. The techniques used here only consider the partitioning between different parts of the spectrum.

Measuring k

The mode partitioning expression for k given in equ. 2 can be simplified as below (equ. 4) using the mean μ and the standard deviation σ of the power present in each mode.

$$k_i = \frac{\sigma_i}{\sqrt{(\mu_i - \mu_i^2)}} \quad (4)$$

Ogawa³ used k to evaluate the mode partitioning of a modulated laser from pulse to pulse. The definition of k given by Ogawa (equ. 2) is also valid for evaluating the mode partitioning of a laser under CW conditions provided that the same assumptions are made.

The apparatus used for k measurements is shown below (Fig. 4). Light from the VCSELs was coupled into the multimode fibre using a pair of lenses in a telescope arrangement (Fig. 4 inset) and from other lasers by direct butt coupling using fibre sockets which had been built into the laser mounts.

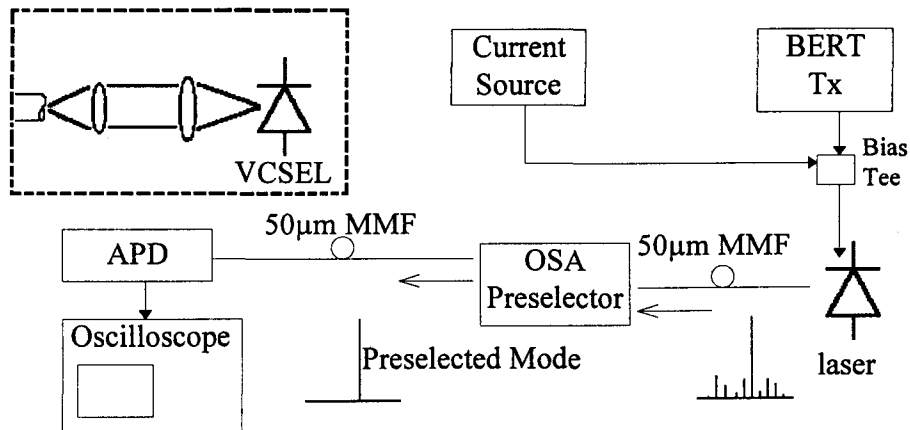


Fig. 4 Measuring k of preselected modes.

Acting as a preselector, the optical spectrum analyser (OSA model HP 79051A) selects a window in the spectrum and allows only those wavelengths lying within this window to pass through to the optical output. The width of the window is determined by - and hence limited by - the resolution bandwidth of the OSA. To measure the k value for a particular mode/mode group (VCSELs), it was preselected and sent on to the avalanche photodiode (Ge or Si APD model BCP 310A). The high speed power fluctuations of the preselected mode were recorded from the APD signal by a digitizing oscilloscope (HP 54720A) sampling at 4×10^9 samples per second.

Using the statistical analysis functions available on the oscilloscope, an estimate could be made of the mean and standard deviation of the APD signal for the preselected mode. Whenever the laser was modulated using a pseudo-random bit sequence (PRBS), the k value was estimated at particular positions in the pattern (Fig. 5). The laser was modulated with a 2^7-1 NRZ PRBS at 1.0625 Gbit/s, unless otherwise stated. Individual 'on' states could be selected from the oscilloscope data using a window which picks out the sampled points on which statistical analysis is to be performed. Whenever long trains of 'on' states were measured, the window was spread across the full length of the 'on' level.

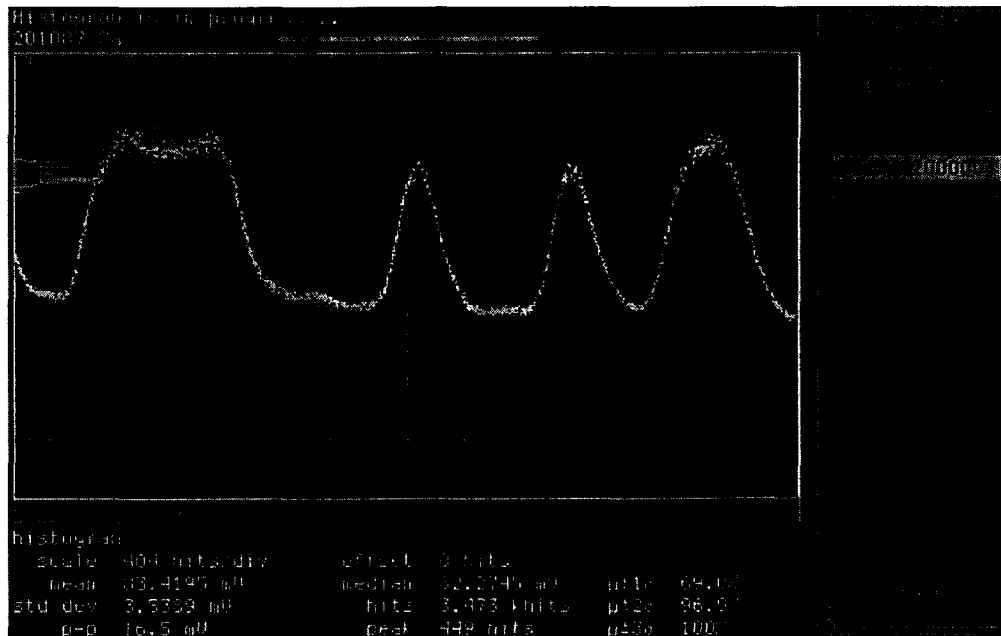


Fig. 5 Single 'on' state in bit sequence being selected using histogram window.

The conversion from the directly measured APD signal into an indirect estimate of optical power was not straightforward. The gain of the APD varies with average optical power and this effect had to be taken into account. This gain variation was measured at each laser wavelength 1300, 850 and 780 nm (Fig. 6). In each case the optical power at the APD was varied using an attenuator or by varying the laser bias, and the mean APD output level was measured.

By adjusting the DC offset of the APD signal the dark current signal could be removed, leaving all other noise, e.g. shot noise to be estimated from the standard deviation of the APD signal. These other noise sources were found to be insignificant for all but the dimmest levels of optical power.

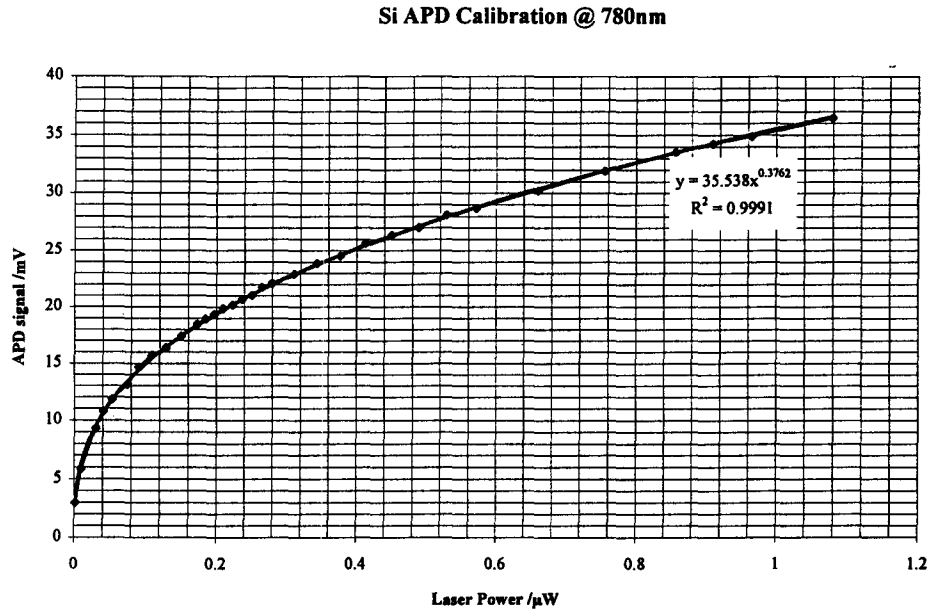


Fig. 6 Si APD gain calibration curve for CD laser wavelength 780 nm

Whenever possible the laser temperature was also controlled using a peltier element and a mounted heatsink. The stability of the laser spectrum was found to be strongly temperature dependent, with small drifts in temperature moving the mode of interest out of the preselection window. As the shifting spectrum could not be monitored with the OSA in preselection mode, care was needed to ensure that data from different modes were taken quickly so that the laser mode structure did not have enough time to change significantly.

Measuring k of VCSELs

There were two different types of VCSEL available for the work reported here, both lasing at 850 nm. These can be separated into oxide and proton bombardment confinement VCSELs where each name refers to the method used to create a current confinement region.

Proton bombardment VCSELs

The number of lasing mode groups is affected by the diameter of the VCSEL aperture. The 5 μm diameter devices, produce a spectrum with only one mode group (Fig. 7). This appears to contain more than one mode, but they are not distinguishable even at this, the sharpest resolution bandwidth of the OSA. The minimum available width of the preselector window would have been at least two divisions on this scale and the edge of this window could not have been placed between the two apparent modes with any confidence.

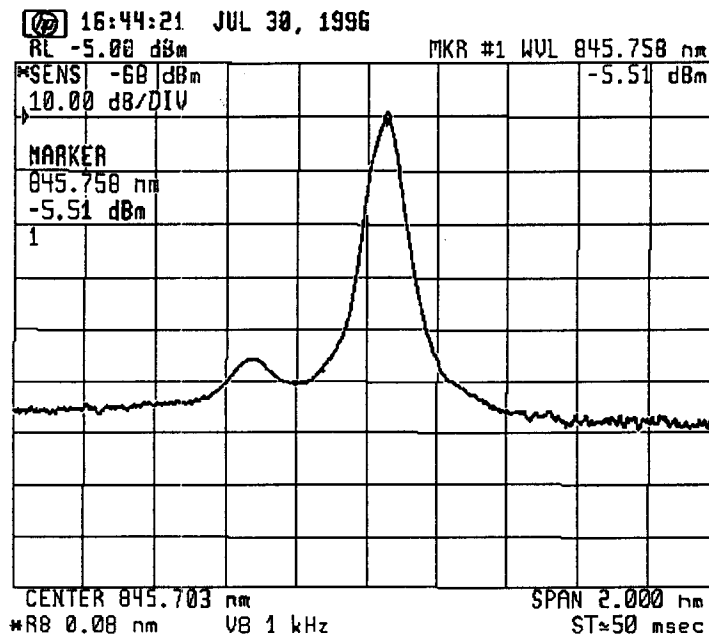


Fig. 7 Spectrum of a 5 μm VCSEL (Note logarithmic amplitude scale).

With only one mode group to measure, the two key assumptions - that the total laser power lies in this mode group and that the total power is constant - frustrate any effort to measure k .

VCSELs with larger diameters have spectra which can exhibit more than one mode group. By carefully observing the numbers of mode groups present under different bias and temperature conditions, it was possible to maintain a spectrum containing two, (or on rare occasions three), mode groups, (Fig. 8) for long enough to perform k measurements. The strong temperature dependence of the VCSEL spectrum can lead to changes in the spectrum within an hour, even when an apparently constant temperature is being maintained by a peltier element.

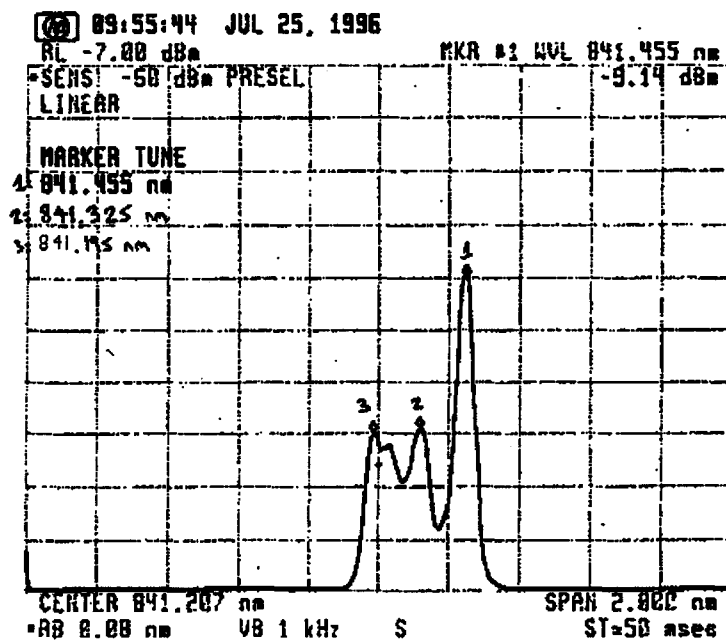


Fig. 8 Spectrum of 15 μ m VCSEL with three mode groups.

After using the Si APD for several weeks, the instrument developed a fault which caused the gain control to follow a sawtooth pattern with a frequency of 100 Hz (Fig. 9). Before its discovery, the sawtooth effect had been increasing the apparent mode partitioning being recorded. This was because measurements of the APD signal were taken at random points in the sawtooth sequence and hence the sampled amplitude values were spread more widely than they should have been. To overcome this it was necessary to trigger the oscilloscope at the APD signal level on the top of the sawtooth pattern and thus eliminate the variation in the recorded APD signal.

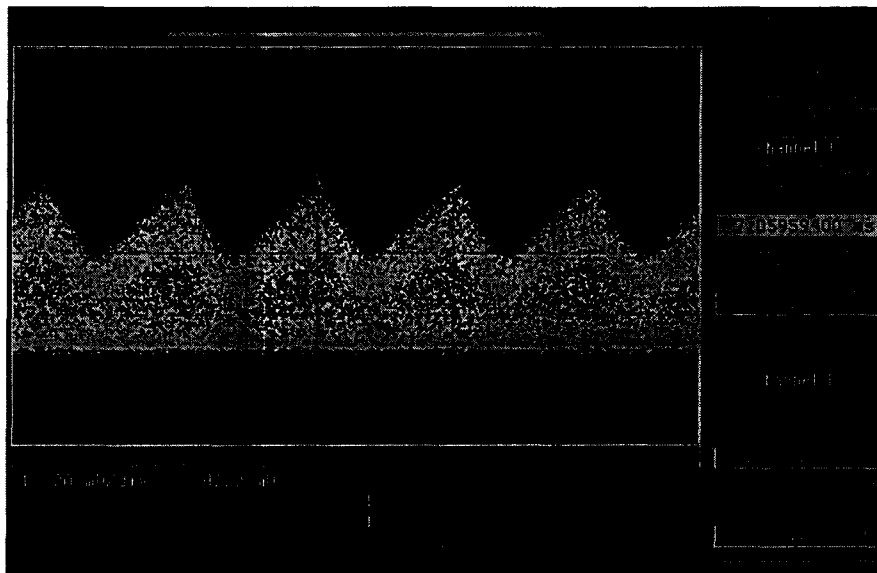


Fig. 9 *Sawtooth variation of APD output with a stable 10 ms period*

Inevitably some of the variation due to mode partitioning was also lost by this triggering method. Any instances when the mode was too weak to produce a high enough APD signal to trigger the oscilloscope would have been neither recorded nor included in the statistical analysis. In practice, the probability of missing events was decreased, as the trigger level was lowered from the maximum possible level, in order to speed up the measurement. This increased the margin of error in the results and reintroduced some variation from the sawtooth. To minimise the error margin, averages were made from multiple readings. Additionally, a further technique allowed an estimate of the fluctuations induced by the sawtooth effect.

Starting from the assumption that the total laser power is constant, the total power of the laser was measured by preselecting a wide enough window to include all the significantly sized lasing mode groups. The exact amount of power coupled was not important, as long as there were no significant fluctuations. The APD signal fluctuations measured from this 'total power' reading, were assumed to be entirely due to the sawtooth effect. The proportional standard deviation of the total power was then used to estimate how much of the fluctuations in the APD signal for individual mode groups was caused by the sawtooth.

Two extreme cases were used to give upper and lower bounds to the estimate of k . The model for the lower bound is based on the assumption that the fluctuations of each mode group are totally dependent on the causes of the fluctuations present in the 'total power' measurement, i.e. mode partitioning is not present and any apparent modal variation is due to sawtooth effects or a fluctuation in the total power of the laser. This dependent case is also possible if the mode partitioning effects are screened out by the trigger setting being so high as to only record the mode in its maximum state.

The upper bound model assumes the total independence of fluctuations in the 'total power' and mode group measurements, i.e. mode partitioning dominates any sawtooth effects or fluctuations in the total power of the laser. The calculations for upper and lower bound values for k are discussed in Appendix A.

Oxide confinement VCSELs

Although oxide confinement VCSELs lase in many more mode groups than the proton bombardment VCSELs (Fig. 10), it was only necessary to measure the k value of one or two powerful modes to obtain a good estimate of the laser k . In the proton bombardment VCSELs, the concentration of power into two or three mode groups allowed the total laser power to be estimated (for the purpose of normalisation), by summing the power measured in each mode group. When measuring the oxide confinement VCSELs only the power in the two most powerful mode groups was measured. To avoid having to measure all the other mode groups individually, a different technique was used to estimate the fraction of the total power present in the two largest mode groups.

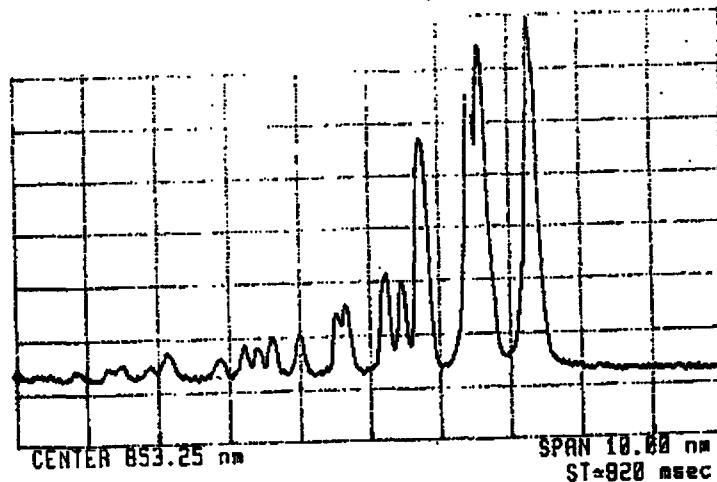


Fig. 10 *Spectrum of an oxide confinement VCSEL*

The APD used for k measurements was replaced by a power meter. The two main modes were simultaneously included in a preselection window 1 nm wide and the power present in this spectral window was measured. A wider preselection window of 5 nm, large enough to include all of the significant mode groups, was used to make an estimate of the total power. The average share of the total power present in the two largest modes was estimated from the ratio of power readings from the 1 and 5 nm preselection windows. As shown above (Fig. 10) most of the lasing power is present within a 5 nm range.

VCSEL Results

The k values for each laser are presented with error margins based on upper and lower limits of 3σ from a particular experiment. VCSELs C and D were measured after the APD sawtooth fault developed. In each case the sawtooth dependent and sawtooth independent estimates for k are given.

VCSEL A

CW results not measured

Under 2^7-1 NRZ PRBS modulation at 1.0625 Gbit/s

- isolated 'on' state $k = 0.34 \pm 0.03$
- long train of consecutive 'on' states $k = 0.34 \pm 0.04$

VCSEL B

CW $k = 0.2 \pm 0.1$

Under 2^7-1 NRZ PRBS modulation at 1.0625 Gbit/s

- isolated 'on' state $k = 0.26 \pm 0.08$
- short train of consecutive 'on' states $k = 0.18 \pm 0.05$
- long train of consecutive 'on' states $k = 0.21 \pm 0.03$

VCSEL C

CW results not measured

Under 2^7-1 NRZ PRBS modulation at 1.0625 Gbit/s

- long train of consecutive 'on' states (dependent) $k = 0.02 \pm 0.02$
(independent) $k = 0.12 \pm 0.03$
- isolated 'on' state (dependent) $k = 0.04 \pm 0.01$
(independent) $k = 0.20 \pm 0.04$

VCSEL D (Oxide confinement VCSEL)

CW results were dominated by APD fluctuations

Under 2^7-1 NRZ PRBS modulation at 1.0625 Gbit/s

- isolated 'on' state (dependent) $k = 0.06 \pm 0.01$
(independent) $k = 0.10 \pm 0.02$
- long train of consecutive 'on' states (dependent) $k = 0.06 \pm 0.04$
(independent) $k = 0.11 \pm 0.04$

Measuring k of a CD laser

Measuring the two or three mode groups of a VCSEL was challenging because the VCSEL spectrum was sensitive to temperature and rapidly changed shape. In contrast, the longitudinal modes in a CD laser only changed amplitude, whilst maintaining a constant wavelength, provided that the temperature and bias were kept constant.

It was not known how many modes would have to be measured to obtain a reasonable estimate the k value of the CD laser. It was known that the most powerful modes have the greatest influence on the laser k , but not how quickly this influence decreases with mode strength. The first 17 modes of the CD laser were measured under CW operation and the first five modes found to be important for evaluating the k value of the laser. Therefore only the first five modes were measured, when the laser was modulated.

Under modulation the number of lasing modes increases and the share of the total lasing power present in the stronger modes decreases. To estimate the fraction of lasing power present in the 5 most important modes, the same method was used as described above for the oxide VCSEL (p. 16).

These CW results were taken before the Si APD developed the sawtooth fault, but the modulation results had to be taken using the triggering technique as used for the VCSEL measurements.

CD Laser Results

The k values for all 17 modes, measured under CW conditions are shown below (Fig. 11). The maximum and minimum values are taken directly from the measurements as there were too few data for a realistic estimate of the error in each measurement. This leads to a CW laser k value estimate ranging from 0.76 (using minimum modal k data) to 0.86 (using maximum modal k data).

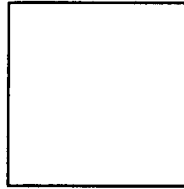


Fig. 11 CD k value spectrum.

The measurements of the CD laser under modulation are given below. In each case only two estimates of the laser k were made, each one based on the five strongest modes.

CD laser k under 2^7-1 NRZ PRBS modulation at 1.0625 Gbit/s

- Long train of 'on' states

Dependent estimates $k = 0.13$ and 0.14

Independent estimates $k = 0.20$ and 0.24

- Single 'on' state

Dependent estimates $k = 0.14$ and 0.30

Independent estimates $k = 0.22$ and 0.47

Measuring k of 1300 nm Fabry-Perot lasers

There was much less optical power in the longitudinal modes of the 1300 nm lasers, than the CD laser modes or in the mode groups of the VCSELs. This limited the measurements which could be performed. The attenuating effect of the preselector often made even the strongest modes too weak to be discernible above the noise of the Ge APD. The modes were also weakened by increasing the bias of the laser (once above threshold), since more modes were excited they took gain and hence power from those already present. The only way of increasing mode strength was to lower

the temperature of the laser. By adjusting the temperature and bias, strong modes could be produced for measuring k under CW conditions. Under PRBS modulation even the strongest modes were too weak, presumably due to spectral spreading. Some measurements were possible with sinusoidal modulation.

To normalise the measurements of those modes which could be detected on the APD, an estimate was needed of their strength relative to the total power of the laser, (the calculations for this are discussed in Appendix A.) To make this normalisation possible the attenuation of the preselector α was measured at 1300 nm. A range of estimates for α was obtained - from 8.6 to 14.5 dB. It was subsequently found that values of α above 14 dB gave non-physical results (negative k values). The value 14 dB was chosen to give the maximum estimate of k , so that all results at 1300 nm would represent the maximum limit on mode partitioning (worst case).

1300 nm Fabry-Perot Results

Laser A k value 0.2 ± 0.03

Laser B k value 0.05 ± 0.02 CW and 0.11 ± 0.01 with RF modulation @ 20 MHz

Laser C k value 0.22 ± 0.02

Laser D k value 0.25 ± 0.05 (at $1.5 I_{th}$) and 0.36 ± 0.05 (at $1.3 I_{th}$) (both at same temp)

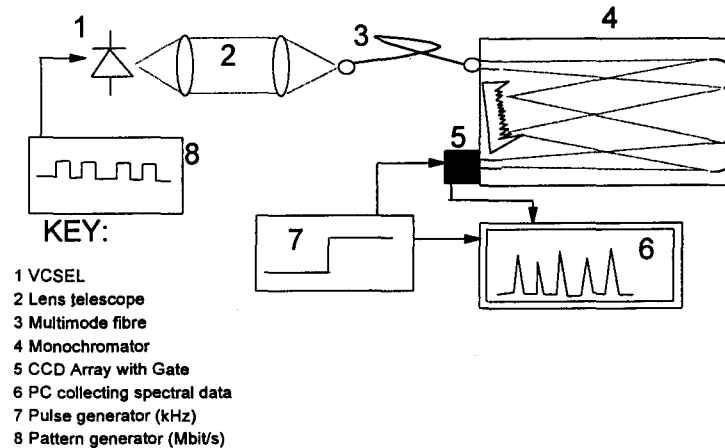
Laser E k value 0.17 ± 0.02

Interpretation and Discussion

It has been possible to measure normalised k values for the preselected transverse mode groups of VCSELs and longitudinal modes of Fabry Perot lasers using different methods of data interpretation, to complement the different experimental techniques needed with different types of laser.

As far as can be estimated from the mode group experiments, the k of the VCSELs does not exceed 0.4. The rule that faster switching single 'on' states exhibit stronger mode partition has no exception among the 4 VCSELs measured, although VCSEL A with the strongest mode partitioning does not seem to be sensitive to the change in switching speed. More reliable data was obtained for VCSELs before the APD fault was present. In general, the best detection system to use would not have any variation in gain with optical power.

A different experimental technique was attempted in the course of this project and it could form the basis of any future work in this area. The apparatus is shown below (Fig. 12).



VCSEL Experiment Apparatus arrangement

Fig. 12 Monochromator based VCSEL experiment

Instead of preselecting the VCSEL mode groups, a monochromator with a high resolution grating is used to spread a spectrum of the VCSELs across an output slit. At this point a gated CCD array captures the spectrum and records relative strengths of the different modes (individual modes may be visible with sufficient resolution). After many snapshots of the laser spectrum, the statistics of each mode could be estimated. These would then be normalised with respect to the total power, which would be evaluated by integrating the power across the entire laser spectrum. If necessary, attenuation would be applied to the laser light, so as not to saturate the CCD. Before the light was passed into the monochromator, the speckle pattern would have to be homogenised using a diffuser, (e.g. a plate of ground glass).

When this experiment was attempted at Bristol University, the grating had a resolution, too poor to resolve mode groups and so no estimate of k could be made.

Summary

VCSELs measured were found to mode partition weakly and consequently had k values below 0.4. A fault with the Si APD affected most of the experiments but it was possible to account for this when interpreting the data.

1300 nm lasers were found to partition similarly weakly, with no laser k above 0.4. However, weak modes on the edge of receiver sensitivity meant that only the strongest laser modes were measured. For this reason, comparative measurements under modulation were not possible as the laser spectrum spread out, reduces modal strength still further.

The CD laser had many modes powerful enough to be easily detected and was found to partition very strongly under CW conditions. The APD fault affected modulation results which clearly indicated (APD faults notwithstanding) a lower mode partitioning than the CW case. As with the VCSELs, faster switching gave stronger mode partitioning.

Further work using a different technique could be used to make a more direct comparison between different laser types and could give a more detailed insight into the spectral structure of VCSELs.

Acknowledgements

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APPENDIX A

The conversion from the APD signal statistics into an estimate of k is discussed below. The selection of upper and lower bounds from the effects of the Si APD sawtooth effect are also explained. These corrections were unnecessary for the Ge APD used with the 1300 nm Fabry-Perot lasers, for which the OSA attenuation was estimated. The calculation from measured data of an estimate for k is also given.

The APD calibration curves for each wavelength are shown below (Figs A1, A2 & A3). The decrease in gain with increasing illumination is shown on the first diagram for 1300 nm. A similar effect is demonstrated by the Si APD at 850 and 780 nm.

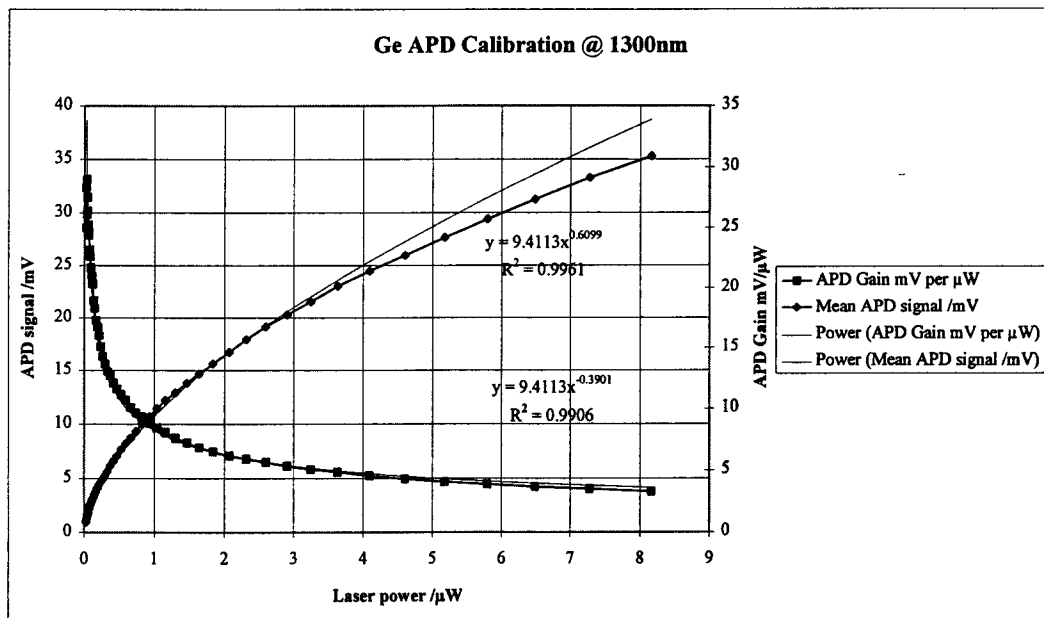


Fig. A1 APD Calibration curve for Ge detector at 1300 nm.

Each calibration curve was approximated using a power curve, the general formula of which is given below.

$$y = Ax^B \tag{A.1}$$

where y is the APD signal in mV, (above the dark current) and x is the laser power

Si APD Calibration @ 850 nm

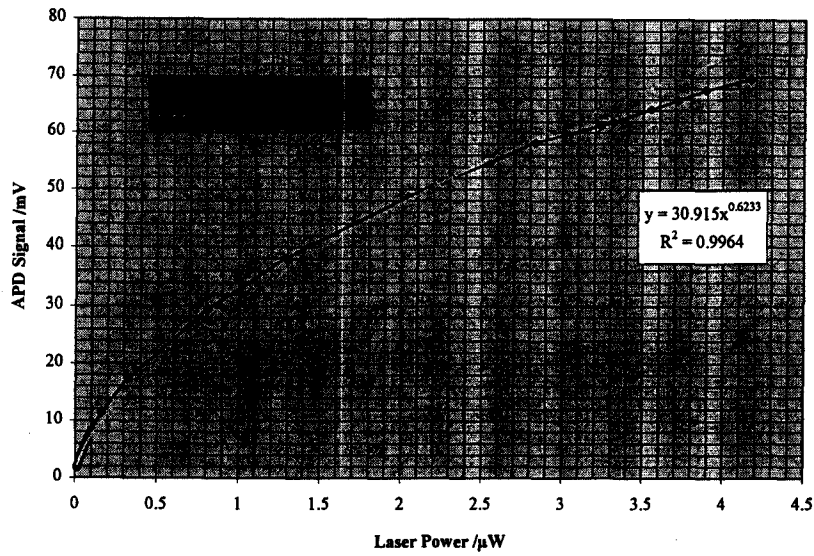


Fig. A2 APD Calibration curve for Si detector at 850 nm.

Si APD Calibration @ 780nm

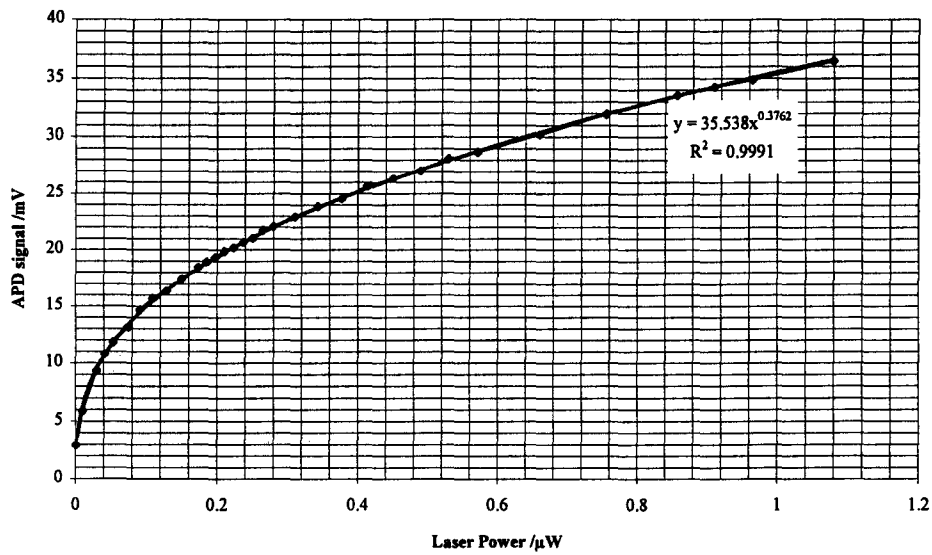


Fig. A3 APD Calibration curve for Si detector at 780 nm.

The APD gain as a function of the laser power (reaching the APD) is given by the ratio of APD signal to laser power.

$$g(x) = \frac{y(x)}{x} = Ax^{B-1} \quad (\text{A.2})$$

The laser power x , was not measured directly however and must be inferred from the APD signal y . Thus the mean APD signal can be used to calculate the mean laser power (mode power amplitude), using equ. A.3.

$$\bar{x} = \left(\frac{\bar{y}}{A} \right)^{\frac{1}{B}} \quad (\text{A.3})$$

The power fluctuations of the preselected mode were so rapid that the gain did not have time to change from one sample to the next. Therefore the gain was estimated using the laser power corresponding to the average value of the APD signal. This was accurate for CW operation as the average power was included in the measurement of the average APD signal. Under modulation, the average power at the detector was not the same as the average power, (calculated from the average APD signal) over the 'on' state window. This resulted in an error in the modulation estimates which was not taken into consideration in any of the measurements. A measure of the average APD signal over a long time period would have provided a more accurate estimate of the average power at the APD and hence the APD gain. Nevertheless, at the high power of the 'on' states, the gain varies only slowly with increasing power so the error will not strongly alter the estimate of k .

The standard deviation of the laser mode σ_x was estimated, (assuming a constant gain), from the standard deviation of the APD signal σ_y .

$$\sigma_x = \frac{\sigma_y}{g(x)} \quad [\text{A.4}]$$

The use of these equations is illustrated below with an example using measured data for the CD laser. In addition an explanation is given of the various methods used to normalise the measurements with respect to the total power of the laser.

CD Laser Example

From one run taking data from 65536 samples for the main mode preselected from a CD laser under CW operation, the APD signal mean was 48.5987 mV and the standard deviation 19.6370 mV. The dark current was already calibrated out.

Firstly laser power at the APD is calculated using the calibration coefficients from the curve of Fig. A.3 and the equation A.3. With $A=35.538$ and $B=0.3762$, the mean modal power was

$$\bar{x} = \left(\frac{\bar{y}}{A} \right)^{\frac{1}{B}} = \left(\frac{48.5987}{35.538} \right)^{\frac{1}{0.3762}} = 2.2979 \mu\text{W}$$

At this power level, the gain of the APD is,

$$g(2.2979) = \frac{48.5987}{2.2979} = 21.149 \text{ mV}/\mu\text{W}$$

With this gain, a change in the APD signal of 19.6370 mV corresponds to a change in optical power of

$$\sigma_x = \frac{\sigma_y}{g(x)} = \frac{19.6370}{21.149} = 0.9285 \mu\text{W}$$

An estimate of the total power was made in this case by summing the mean power level of the 17 most powerful modes. This total came to 2.84995 μW . The mean and standard deviation from this particular measurement were normalised with respect to the total power,

$$\bar{x}_{norm} = \frac{\bar{x}}{x_{total}} = \frac{2.2979}{2.84995} = 0.8063$$

and likewise

$$\sigma_{x(norm)} = \frac{\sigma_x}{x_{total}} = \frac{0.9285}{2.84995} = 0.3258$$

With these normalised values, k can be estimated using equation (4)

$$k = \frac{\sigma_{x(norm)}}{\sqrt{\bar{x}_{norm} - (\bar{x}_{norm})^2}} = \frac{0.3258}{\sqrt{0.8063 - 0.6501}} = 0.8244$$

Estimating the total power

Other methods were used to estimate the total power, when a significant number of modes could not be measured. At 1300 nm, the OSA attenuation α was used to scale up the estimated mean power and standard deviation values, to estimate their strength before entering the OSA. For example a mean power of $0.3871 \mu\text{W}$ at the APD, corresponded (with an α of 14 dB) to a modal mean power of $9.722 \mu\text{W}$ direct from the laser. This was normalised with reference to the total power $52.48 \mu\text{W}$ (measured using a power meter directly connected to the laser). The same scale factor was used on the standard deviation.

One other method of estimating the total power, was used with the VCSELs and the CD laser under CW operation. This method is described on p. 16.

K estimates dependent and independent of the APD sawtooth

To remove the effect of the APD sawtooth as described on p. 14, the following equations were used for the assumptions of totally dependent and totally independent fluctuations.

In each case the normalised standard deviation of the total power $\sigma_{\text{total power (norm)}}$ was measured.

Dependent fluctuations

Assuming all fluctuations in the APD signal for a preselected mode had a common cause with fluctuations in the APD signal for a total power reading, then the correction to the normalised standard deviation of modal power is given by the difference between the modal standard deviation and the standard deviation of the total power (scaled with respect to the normalised size of the preselected mode).

$$\sigma_x(\text{corrected}) = \sigma_x(\text{uncorrected}) - \bar{x}_{\text{norm}} \sigma_{\text{totalpower(norm)}} \quad (\text{A.5})$$

Independent fluctuations

Assuming all fluctuations in the APD signal for a preselected mode had no common cause with fluctuations in the APD signal for a total power reading, then the correction to the normalised standard deviation of modal power is given by the difference between the modal variance and the variance of the total power (scaled with respect to the normalised size of the preselected mode).

$$\sigma_x^2(\text{corrected}) = \sigma_x^2(\text{uncorrected}) - \left(\bar{x}_{\text{norm}} \sigma_{\text{totalpower(norm)}} \right)^2 \quad (\text{A.6})$$

