MEASUREMENT OF VCSEL MODULATION SIDEBAND FREQUENCY RESPONSE USING A HETERODYNE DETECTION METHOD

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Abstract

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A heterodyne measurement system was constructed to measure the frequency response of Vertical Cavity Surface-Emitting Lasers (VCSELs). As optical spectrum analyzers do not have sufficient resolution to measure radiofrequency modulation sidebands at optical carrier frequencies, some method of frequency down-conversion is necessary to measure the response. Currently, the standard method of measurement is the use of a Vector Network Analyzer (VNA). However, the heterodyne measurement system, which shifts the carrier frequency into the radiofrequency range, has the advantage of being substantially less expensive than a VNA. The VCSEL response was also simulated in MATLAB by a numerical solution of the semiconductor rate equations, and this simulation data was used to evaluate the heterodyne measurement system. The efficacy of the heterodyne system was also further tested by comparison with results measured using a VNA.

Tests were performed on free-running VCSELs in the telecommunications band (roughly 192 THz). It was found that the rolloff rates and knee frequencies of the two measurement methods were in good agreement both with each other and with the simulation predictions. It is concluded that the heterodyne measurement method designed in this project is effective for measuring the frequency response of VCSELs at frequencies up to 20 GHz. Recommendations are provided for further extension and improvement of the measurement method as well as the analysis of simulation data to higher frequencies, and to further improve the accuracy and repeatability of the heterodyne measurement technique.
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1. Introduction

The Vertical Cavity Surface-Emitting Laser (VCSEL) is a semiconductor laser diode that emits light perpendicular to its top or bottom surface, rather than its edge. Now that fabrication techniques have advanced sufficiently to allow for their production, VCSELs are poised to supplant edge-emitting lasers in applications such as optical fiber data transmission. Therefore, it is desired to characterize the modulation frequency response of VCSELs. At telecommunications optical carrier frequencies (approximately 192 THz), the resolution of Optical Spectrum Analyzers (OSAs) is not sufficient to resolve the radiofrequency (RF) modulation sidebands. One piece of equipment able to measure the VCSEL frequency response is a Vector Network Analyzer (VNA); however, these are very expensive to purchase.

This project involves the development of an optical heterodyning technique to down-convert the optical carrier frequency into the RF range. In this range there exist inexpensive RF spectrum analyzers (RFSAs) that can measure the spectrum of the optical signal; by varying the modulation frequency, the frequency response of the VCSEL can be obtained. Specifically, a heterodyne measurement setup was built, and an experiment conducted on a free-running VCSEL. The results from the heterodyning setup are compared with a measurement taken with a VNA, as well as spectral analysis of simulation data obtained by a numerical solution of the semiconductor laser rate equations.

This report discusses the heterodyne technique that was implemented to measure the frequency response of the free-running VCSEL. The reader is assumed to have general
technical competence, without specialized knowledge on radiofrequency communications or heterodyne measurement. Therefore, the discussion includes a description of the general principles of heterodyne detection, as well as background on VCSELs in general. The methods in each part of the project (heterodyne measurement, VNA measurement, and model simulation) are then described. The equipment used in the experiments is outlined, with an emphasis on how they were employed to implement the aforementioned methods. The results of the measurements are presented and interpreted, providing information both on the frequency response of the VCSEL, as well as the efficacy of the heterodyne measurement technique by comparison with a measurement taken using the VNA. Discrepancies between the heterodyne measurement, VNA, and model are noted, and possible sources of error hypothesized. With the failure of the VCSEL that measurements were performed on, the sources of error could not be investigated further, and thus a detailed error analysis was deemed outside the scope of this report. To that end, the conclusions drawn will focus primarily on the suitability of the heterodyne measurement technique for frequency response measurement of VCSELs, as well as the results of the aforementioned measurement. Recommendations for continued work focus on the possibilities for further characterization of the measurement method by future project groups and other students. Appendices for reference include code used to automate the measurement equipment, an experimental protocol emphasizing techniques for VCSEL-to-fiber coupling alignment, and code used to analyze experimental and simulated data.

In addition to satisfying Project Laboratory requirements and informing the project sponsor on the activities accomplished this term, the intended audience for this report is
future students. This report should serve as an introduction to some of the equipment and techniques involved in experiments performed in the UBC ECE Optoelectronics laboratory, as well as provide specific information and reference on hardware operation, software interfaces, and data processing.
2. Discussion

2.1. Background and Theory

This section is primarily concerned with familiarizing the reader with VCSELs, as well as providing some background on the generation of sidebands through amplitude modulation, and detection of radiation through heterodyning. It is intended for the reader with little to no background in the field; this section may be safely skipped if the reader is already familiar with amplitude-modulated signals and heterodyne detection.

2.1.1. Vertical Cavity Surface-Emitting Lasers (VCSELs)

A Vertical Cavity Surface-Emitting Laser (VCSEL) is a semiconductor laser diode that emits light perpendicular to the upper surface of the semiconductor wafer of which the laser is composed. This is in contrast to standard "edge-emitting" lasers, which emit light from a cleaved surface of a semiconductor wafer.

The laser resonator for a VCSEL consists of two distributed Bragg reflectors (DBRs). These are dielectric mirrors that are positioned parallel to the surface of the wafer, and have a reflectivity above 99%, on account of their design. The active region on the laser consists of one or more quantum wells. Typically, the active region of a VCSEL is composed of Gallium Arsenide (GaAs) with the DBRs are composed of Aluminium Gallium Arsenide (AlGaAs). When electrical contact is made with the active region, photon generation occurs, which results in the emission of light. It is possible to pump the active region through the use of an external laser operating at a wavelength shorter than the VCSEL, and this will result in photon generation without the need for electrical contact. Figure 1 depicts the structure of a typical VCSEL device.
Compared to conventional edge-emitting lasers, VCSELs offer several benefits, such as lower power consumption on account of the high reflectivity of the DBRs, the ability to test the properties while still on a wafer (i.e. they do not have to be cut or mounted before they can be tested), and the ability to be used in two-dimensional arrays. More importantly, VCSELs have a high coupling efficiency with optical fibers, making them desirable for use in the telecommunications industry. One limitation of VCSELs that has yet to be solved is an overall lower output power compared to conventional edge-emitting diode lasers; however, this disadvantage is likely to be surmounted as VCSEL technology continues to mature.

Two different models of VCSELs were tested over the course of this project; both consist of the materials listed above, and produce light at a wavelength close to 1550 nm, the infrared (IR) range used most widely by the telecommunications industry. The first type consisted of only a semiconductor wafer, and coupling to fiber was through the use of special probe; the second type was in a TO-56 canister package, which consists of a laser
mounted into a metal canister, with pins sticking out for easy electrical contact for voltage tuning and electrical modulation.

2.1.2. Sideband Modulation and Heterodyne Detection

The amplitude of a VCSEL's emission may be varied by varying the electrical current supplied to it. As with any amplitude modulation of a carrier wave, such amplitude modulation of a VCSEL's emission produces sidebands in the emitted light. If the frequency of the unmodulated VCSEL (the optical carrier) is $\nu_1$, and an electrical signal of frequency $f_s$ is applied, the sidebands have frequencies $\nu_1 + f_s$ and $\nu_1 - f_s$.

Typical experiments to date have used an optical carrier of about 192 THz, modulated on the order of 10 GHz, and used spectral analysis of the modulated carrier to measure the amplitudes of the sidebands. With a frequency difference between carrier and sidebands that is so small relative to the carrier frequency, it is difficult to distinguish the carrier and sidebands in the spectrum. Experiments to date have been able to directly measure the properties of the modulation in spite of the high-frequency carrier by using a VNA or other expensive, specialized equipment. However, recent work has shown that optical heterodyning can be employed to effectively down-convert the signal to frequency ranges more easily measurable by conventional measurement equipment.

The modulated carrier is mixed with light from a reference source and the mixed signal is fed into a photodiode. By responding to the amplitude envelope of the mixed signal, the photodiode will produce the beat frequencies of the mixed signal as its electrical output: That is, if the modulated optical carrier has frequency components $\nu_1, \nu_1 + f_s$, and $\nu_1 - f_s$, as detailed above, and it is mixed with a reference source of frequency $\nu_2$, the spectrum
of the photodiode's output will include frequencies $v_1 - v_2$, $v_1 + f_s - v_2$ and $v_1 - f_s - v_2$.

Of course, this output is also limited by the frequency of the response of the photodiode. Since the photodiode has a flat frequency response up to 60 GHz, the experiments conducted in this project will have a frequency response in the 20 GHz range dominated by the response of the VCSEL. Figure 1 and Table 1 together describe a simplified version of a heterodyne detection system, and the signal frequencies that are present at important points of the setup.

![Figure 2: Simplified block diagram of a heterodyne setup.](image)

<table>
<thead>
<tr>
<th>Fiber Optical Frequencies</th>
<th>Electrical RF Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: $v_1 - v_2$, $v_1 + f_s$, $v_1 - f_s$</td>
<td>A: $f_s$</td>
</tr>
<tr>
<td>2: $v_2$</td>
<td>B: $v_1 - v_2$, $v_1 + f_s$, $v_1 - f_s - v_2$</td>
</tr>
<tr>
<td>3: $v_1$, $v_2$, $v_1 + f_s$, $v_1 - f_s$</td>
<td></td>
</tr>
</tbody>
</table>

Note that the frequency difference $f_s$ between the carrier and the sidebands is preserved, but the carrier frequency is shifted down to $v_1 - v_2$. Thus, the frequency difference between sidebands and carrier is larger relative to the new carrier frequency and the sidebands are easier to distinguish.
2.2. Methods

This section details the procedures and techniques for measurement and simulation work done over the course of the project. Specifically, it outlines the MATLAB simulations used to model the operation of the VCSELs under modulation, the VNA measurements of the $S_{21}$ parameters of the VCSELs, and the setup used for heterodyning measurements.

2.2.1. MATLAB Simulations

[1] describes the semiconductor rate equations that have been previously developed by the project sponsor. Accordingly, MATLAB software to numerically solve the differential equations had already been developed by the time the project started. As provided, the program returned a time-domain description of the resulting electric field of the light output. To generate data comparable to the experimental work, Fourier analysis was performed on the resulting time-domain solutions to extract spectral information.

As MATLAB had already been used to implement the solution of the differential equations, it was a natural choice to use for the analysis of the data as well. As the default implementation of the Fast Fourier Transform (FFT) in MATLAB is designed for generality, the generation of a power spectrum from this requires several steps, such as scaling of the resultant peak amplitudes and frequency axis. Accordingly, `spec.m` was developed to generate a power spectrum from the time-domain data. Its code is included in Appendix D, and its primary purpose is to perform the scaling of amplitudes and frequency values to produce a spectrum from arbitrary time and amplitude data. The efficacy of `spec.m` was evaluated by checking its output when given a 100 Hz sine wave input whose amplitude is modulated by a 10 Hz sine wave. As per the theory mentioned above, it is expected that the resulting spectrum would have a carrier frequency at
100 Hz, plus two sidebands at, at 90 and 110 Hz. The output is displayed in Figure 3, demonstrating the function of \textit{spec.m}.

![Testing of spectral analysis routine](image)

\textbf{Figure 3: Power spectrum of 100 Hz sine wave modulated at 10 Hz, using \textit{spec.m}.}

The FFT algorithm also depends on the sampled time points to be evenly spaced. Originally, the differential equation solver provided by the project sponsor did not observe this restriction on its solutions. It was thought that evenly spaced data could be adequately recovered by interpolation of the non-uniform time solution. This was attempted, without success – interpolation caused severe harmonic distortion in the power spectrum, as seen in Figure 4.
While it is possible to implement Fourier techniques from first principles on non-uniform time data [2], the time constraints on the project made retooling of the modeling software to generate evenly spaced time data the better option. After consultation with the project sponsor it was decided to modify the original differential equation solver, in order to force it to output uniformly-spaced time samples. A Blackman window was also applied to the uniform time-domain data, in order to improve the signal-to-noise ratio. An example of a spectrum preprocessed in this manner is shown in Figure 5; note that the carrier and sidebands are clearly distinguishable, as opposed to the previous case. The higher-order harmonics from the nonlinearities of the VCSEL itself die out quickly, as expected – there is no notable harmonic distortion as seen in the previous case. For the modulation frequencies of interest (on the order of GHz or tens of GHz), the sidebands are readily distinguishable; hence this spectral analysis method was used to obtain the frequency response of the VCSEL. Simulation data was generated for a set of modulation frequencies ranging from 100 MHz to 20 GHz. The carrier frequency, originally in the optical range (1550 nm ~ 192 THz), was shifted down to roughly 20
GHz. This is equivalent to a phase shift in the time domain by a complex exponential [3], so it has effect on the relative position of the two sidebands with respect to the carrier. That is, the difference in frequency between the carrier and the two sidebands will remain equal to the original modulation frequency, regardless of the optical carrier frequency. This is also easily seen in Figure 5.

![Image of power spectrum from evenly-spaced time data](image)

**Figure 5: Power spectrum from evenly-spaced time data**

It was found that through this method of analysis, there was a constant offset of the carrier frequency of approximately 3.3 GHz from the expected value, regardless of the choice of carrier frequency when forming the expression for the electric field. The invariance of relative sideband position means that the carrier frequency is not important to the analysis, and as the offset is constant with respect to modulation frequency, the only adjustment that had to be made was to the initial conditions for peak fitting.
Peak fitting was performed with modified code based on the MATLAB Curve Fitting Toolbox. The resulting program is included in Appendix D as specfit.m. The three peaks of highest intensity are fit to Gaussian lineshapes. Good initial conditions for peak position are easily found because of the known peak locations – namely, the carrier frequencies of the operator’s choosing, and above and below the carrier by the modulation frequency, for the sidebands. The result of this fitting is illustrated by an example in Figure 6. Note that while the fit equations do not take into account the nonzero baseline, the fit converges well for the position and amplitude of the carrier and sidebands, making possible an analysis of their relative intensities.

![Figure 6: Fitting carrier and sidebands to three Gaussian lines.](image)

This method was applied for a set of modulation frequencies between 100 MHz and 20 GHz to find the amplitude of their carrier and sideband peaks. Each sideband was normalized to the intensity of the carrier by taking the ratio in linear units, or the
difference in a dB scale. The set of these sideband amplitudes constitutes the simulated modulation frequency response of the VCSEL. The results of the simulation data analysis as well as comparison with experimental data are covered in Section 2.4.

### 2.2.2. Heterodyne Measurement

Figure 7 shows the setup used for the heterodyne measurements. A Keithley 2602 Sourcemeter provided the DC bias current for the VCSEL, and an HP 83732B Synthesizer provided the RF modulation current. RF current was carried to the VCSEL via a 10dB attenuator and approximately 2m of coaxial cable, fitted with SMA connectors, and the DC and RF currents were mixed at a bias tee before being applied to the VCSEL. The optical output of the VCSEL was amplified by an Avanex Erbium-Doped Fiber Amplifier (EDFA) before being sent to a three-port coupler, where it was mixed with the signal from a local oscillator.

The local oscillator laser was an HP 8164A Lightwave Measurement System; its output was fed to the coupler via a polarization controller.

The combined VCSEL-local oscillator optical signal was fed to a Newport XPDV2020R detector. The RF electrical output of the detector was coupled to the input of an Agilent E4407B spectrum analyzer. An Agilent E8361A VNA served strictly as a GPIB controller for the spectrum analyzer. Section 2.3.4 contains further details on computer control of the experiment; automatic control of the RF synthesizer had not yet been implemented when the data presented in this report was taken.
Various combinations of equipment were tried before settling on the setup described here. A distributed feedback (DFB) laser was tried as the local oscillator, but the HP8164A was found to produce spectra with narrower linewidths. An Oprel EDFA was also available, but the Avanex was found to operate more reliably and to have higher gain and lower noise. An HP 70900 radiofrequency spectrum analyzer (RFSA) was available which had a noise floor approximately 10dB lower than that of the E4407B for a given bandwidth setting, but the E4407B's more modern implementation of GPIB allowed faster development of control scripts.

Adjustments to the polarization controller were found to have no effect on the heterodyne spectrum. The polarization controller was included to reproduce the setup described in [4].
For the trial that produced the results presented in this report, the VCSEL DC bias was 4.00 mA. RF modulation was nominally -25dBm for frequencies from 1 to 13 GHz and -15dBm for frequencies from 14 to 20GHz (these power levels were based on 50 ohm nominal impedance). The local oscillator was set to deliver +10 dBm.

2.2.3. Vector Network Analyzer Measurement

The setup for the VNA measurement was similar to that for the heterodyne measurement, except that one port of the VNA replaced the RF signal generator and the other port replaced the RF spectral analyzer, and the local oscillator was shut off. With the local oscillator off, the signal at the input of the detector was exactly the optical output of the VCSEL, neglecting losses in the polarization controller. By responding to the intensity of the incident light, the photodiode detected the modulation frequency of the VCSEL signal, or equivalently, the beat frequency between either sideband and the carrier.

The VNA was set to measure the S-parameter $S_{21}$: it stepped through a closely-spaced series of modulation frequencies, recording the ratio of input-to-output voltage of the VCSEL-detector system at each frequency.

2.3. Equipment

This section provides a description of the major instruments used in the heterodyning measurements of the VCSELs. The primary equipment detailed includes the lasers, the vector network analyzer, and the radiofrequency spectrum analyzers. As well, the MATLAB code written to automate the spectral measurements is detailed.
2.3.1. Vector Network Analyzer

An Agilent E8361A vector network analyzer was used as the main equipment hub for the measurements, since it functions as both a network analyzer and the computer controller for running MATLAB (see Section 2.3.4). As a network analyzer, the instrument can measure the reflection and transmission of electrical and optical networks connected to its two ports. Of specific interest in this project was the $S_{21}$ parameter, which gives a ratio of the transmission through a device connected between port 2 and port 1. This transfer characteristic is of vital significance to characterization of a device under test (DUT), and typically the frequency response of a device is described largely by the behaviour of the $S_{21}$ parameter.

![Figure 8: Agilent E8361A Vector Network Analyzer (VNA).](image)

In order for the $S_{21}$ measurements to provide any value, the VNA must first be calibrated through the following procedure:

- Connect a fiber optic cable between the two ports.
• In the network analyzer software, select Calibration → Calibration Wizard

• In the Calibration Wizard, select UNGUIDED → Response → THRU

• Click NEXT to finish the calibration

When the $S_{21}$ parameter data is saved, it is stored in PRN file format. In order to plot the data for analysis, it must first be converted into a simplified DAT format, which strips out the unnecessary formatting present in at PRN file. A MATLAB script (prn2dat.m) was written to do the conversion, and can be found in Appendix D.

2.3.2. Lasers and Supporting Equipment

The HP 8164A Lightwave Measurement System is a control and display mainframe that can be fitted with a variety of source and sensor modules. The 8164A at the UBC ECE Optoelectronics Lab is fitted with an 8162A 1550 nm tunable laser.

![Figure 9: HP 8164A Lightwave Measurement System with 8162A tunable laser.](image)

In a distributed feedback (DFB) laser, feedback is provided not by mirrors but rather by periodic, distributed perturbations of some bulk quantity (such as the index of refraction)
in the gain medium. The wavelength of a DFB laser can be tuned by adjusting the laser’s temperature, on account of both temperature dependence of the gain medium’s index of refraction and thermal expansion.

The DFB laser used in these experiments is a JDS Uniphase CQF935/908, capable of operating over the temperature range corresponding to wavelengths between 1527 and 1610 nm. It is equipped with two Newport model 3040 temperature controllers, one for the gain medium and one for the substrate. The project sponsor recommended limiting the bias current applied to the CQF935/908 to 250 mA and keeping the temperatures in the range of 0 to 90°C. The normal voltage drop across the DFB at 250 mA bias is approximately 1 V and optical output power is approximately +5 dBm. The transient response of the temperature controllers is adjustable.

An Erbium Doped Fiber Amplifier (EDFA) is an optical amplifier comprising a silica fiber doped with erbium ions. As in a pumped laser, the electrons of the erbium ions are excited by radiation from a source such as a semiconductor laser. When a traveling wave propagates into the EDFA, it stimulates the emission of photons by the excited electrons and the wave is amplified [5].
The Avanex EDFA used in the present optical setup is not marked with a model number. It has a gain of approximately 18dB.

![Figure 11: Avanex Erbium-Doped Fiber Amplifier (bottom)](image)

The HP8163A Lightwave Multimeter is, like the 8164A, a control and display mainframe that can be fitted with a variety of source and sensor modules. This specific 8163A is fitted with HP81525A optical head, a sensor module with an InGaAs sensor element. The system is calibrated to measure the optical power incident on the sensor.

The HP 83732B synthesized signal generator is an RF signal generator capable of operating over the frequency range 10 MHz – 20 GHz. It is capable of pulse, scan, frequency, phase, and amplitude modulation, but for the experiments described in this report, it was used only to produce an unmodulated RF signal.

The Keithley 2602 Sourcemeter combines the functions of a precision current or voltage source and a digital multimeter. It is also capable of serving as a waveform or pulse generator, although that capability was not used in the research presented in this paper.
2.3.3. Radiofrequency Spectrum Analyser (RFSA)

A spectrum analyzer is an instrument used to decompose an electrical or optical signal in the time-domain into a spectrum of the frequency components which make up the signal.

Two spectrum analyzers were used in this project – both radiofrequency spectrum analyzers (RFSA) – an Agilent E4407B and an HP 70900B. The HP 70900B was originally used, as it offers a lower noise floor, but it is prone to crashing when basic GPIB commands (such as *IDN?) are sent to it (although device-specific commands do not cause issues). The Agilent E4407B is a newer RFSA with a slightly higher noise floor, but is much more amenable to GPIB interfacing.

![Figure 12: HP 70900B (left) and Agilent E4407B (right) RFSAs.](image)

2.3.4. Heterodyne Measurement Control and Automation

As mentioned above, the sidebands of the VCSEL under amplitude modulation were observed using an RFSA. In order to record the data from the spectra produced (for future analysis), a MATLAB script (rfsa.m, see Appendix B) was created. The MATLAB Instrument Control Toolbox provides a variety of drivers to allow MATLAB to communicate and control measurement equipment (such as the RFSA or the signal generator) through different measurements protocols; of specific use to the project were the GPIB drivers. GPIB (General Purpose Interface Bus) connections use the IEEE 488.2
communications standard, and the connectors are standard on nearly all modern measurement equipment. Owing to its commonality, GPIB was chosen to control and automate the various instruments in the laboratory. The code was executed from the VNA, which is capable of running MATLAB through the Windows XP operating system, and this was designated as the ‘controller’ for all communications.

The initial version of rfsa.m was a basic downloader – that is, it would simply download the amplitude value at each point in the frequency spectrum, producing a .DAT file containing these values. For early measurements, this provided sufficient functionality, but it took a long time to gain useful data, as the user had to manually zoom in on each of the sidebands, which involved changing both the start and stop frequencies of the measurement span. The second version of the script increased the automation of data collection, by first recording the full spectrum from 10 MHz to 26 GHz, and then adjusting the frequency values to zoom in on each of the sidebands, and record the spectra. The final version of the code automatically set the modulation frequency on the signal generator; the script was extended so that the user could set a span of modulation frequencies over which to measure, and the program would loop through each of these frequencies, recording spectral data (of the full spectrum, and of each sideband) at every value. A flow diagram describing the operation program is provided in Figure 13; a detailed step-by-step description of the code is contained in Appendix A and the complete code is included in Appendix B.
Figure 13: Experiment control program flowchart.
2.4. Results

This section describes the results from each part of the project separately. The predictions from the simulations are first presented, followed by the heterodyne measurement experiment results. Lastly, a similar measurement taken by a VNA is also presented for comparison with the heterodyne system. Section 2.5 brings together the separate results for further comparison and evaluation of the heterodyne measurement technique.

2.4.1. MATLAB Simulation Results

As described in Section 2.2.1, simulation data was generated in MATLAB using a solution to the semiconductor laser rate equations developed by the project sponsor. Fourier analysis of the resulting time-domain data yielded power spectra, for which the relative amplitudes of the sidebands, with respect to the carrier, were extracted for each modulation frequency. The modulation frequency was varied between 100 MHz and 20 GHz. Beyond that, the ordinary differential equation (ODE) solver did not provide sufficient time points to keep both sidebands in the field of view of the spectrum, and time constraints precluded modification of the program to either evaluate the equation for more time points, or to extend the (periodic) solution in time to allow for more frequencies to be represented in the FFT. Nevertheless, as 20 GHz was also the frequency limit for the heterodyne experiment, this frequency span was useful for comparing with results from measurement techniques to evaluate their efficacy. Figure 14 shows the simulated frequency response of the free-running VCSEL, plotted linearly in frequency, with units of dB.
As expected, the upper and lower sidebands exhibit low-pass behaviour with an enhancement effect at the knee frequency of approximately 5 or 6 GHz. The high-frequency portion of the response (i.e. above the knee frequency) can then be fit to a power law relationship to find the expected rolloff rate. A power law relationship is linear on a log-log scale, with the rolloff (in dB/decade) being the proportionality constant. As shown in Figure 15, it was found that the rolloff of intensity is -53.25 dB/decade and -56.12 dB/decade for the upper and lower sidebands respectively. Of course, the vertical displacement of the curve is dependent on multiplicative constant factors in the expressions for sideband and carrier amplitude in linear units. The shape and slopes of the lines, however, should be preserved through any discrepancies between the model parameters and experimental results.
2.4.2. Heterodyne Measurement Results

A similar analysis technique to the simulation data was used for measurements made using the heterodyne system. As described earlier in Sections 2.2.2 and 2.3.4, the result of the heterodyne measurement at each modulation frequency was three spectra: One at full span centered on the carrier frequency, and two centered on the upper and lower sidebands respectively. Figure 16 illustrates the process. Two results from the heterodyne measurement that differed from the simulated case are that the linewidth of the heterodyned spectra are extremely sharp (on the order of 3 data points), and also that the location of the peak shifts substantially with time. The result of this is that the fitting routine to find peak amplitudes used for the simulation data cannot be applied for this data. Being that the peaks were of very narrow linewidth, the maximum value of the spectrum in the range of the peak was taken to be the amplitude. While this is clearly not an optimal solution in terms of accuracy and repeatability (Section 4 contains further
information and recommendations on improving this experiment), the analysis continued using these as peak amplitudes.

Figure 16: Illustration of zooming-in on sidebands from full span spectra.

These peak amplitudes are treated in the same way as in the case for the simulation – as they are already in logarithmic units, each sideband amplitude is subtracted from its respective carrier amplitude. These normalized figures are then plotted against modulation frequency to produce an analogous plot to Figure 14. Figure 17 shows the frequency response of the VCSEL measured using heterodyning. Qualitatively, the enhancement effect at 5 or 6 GHz is again seen, as well as low-pass behaviour, namely the rolloff at higher frequencies. Again, the information can be plotted in a log-log plot, making the expected power law relationship appear as a linear relationship in dB/decade.
Figure 17: VCSEL modulation sideband frequency response (heterodyne method).

As with the simulation data, a linear relationship was found for the log-log plot beyond the response knee. Figure 18 plots the linear fit of the rolloff characteristics against the data points. The proportionality was found to be -60.81 dB/decade for the upper modulation sideband, and -65.51 dB/decade for the lower sideband. The discrepancy in rolloff rate between the upper and lower sidebands is qualitatively similar to the simulation case, though it is expected that for free-running VCSELs the sidebands should be symmetric, regardless of frequency. The second fit parameter corresponds to proportionality constants related to frequency-independent amplification/attenuation, and would depend largely on the frequency response of the measurement system as well as the device under test (DUT).
2.4.3. VNA Measurement Results

Compared to the two measurement schemes above, measuring the frequency response using the VNA is rather simple. After the calibration procedure described above, the VCSEL setup is connected to the VNA, with the RF input also provided by the output port of the VNA, and the optical power coupled to the VNA input via a photoelectric detector. The resulting $S_{21}$ measurement is shown in Figure 19. Clearly there are some differences between the resulting data set and the data from simulation and the heterodyne measurement. The frequency span of the measurement extends to 67 GHz, as opposed to the 20 GHz limit from the heterodyne setup (limited by the RF source) and the simulation data (limited by the robustness of the fitting method and spectral field of view). Moreover, the $S_{21}$ measurement of the VNA does not distinguish between the sidebands. That is, the intensity shown represents the intensity of the sum of the two sidebands relative to the input power. Assuming symmetric sidebands (which should be
true for a free-running laser), the result is a multiplicative factor which translates to a vertical shift of the entire response on the dB scale.

A power law fit was performed on the rolloff region of the response, as with the simulation and heterodyne experiment data. Figure 20 shows the result of this fit (shown in red), which ascribes a value of -80 dB/decade to the rolloff. In addition to the low-frequency region, the noisy region close to the detection limit was also not included in the fitting routine. A second linear fit was performed, this time also excluding the frequencies outside the range of measurement for the heterodyne method and the simulation data. This fit, shown in black, on the range of frequencies between 8 and 20 GHz, resulted in a rolloff of -58.04 dB/decade.
2.5. Summary and Discussion of Results

A qualitative comparison of the heterodyne technique with respect to simulation predictions and VNA measurement is encouraging. All three responses show low-pass behaviour with a cut-off frequency ranging from 5-10 GHz. A plot showing the three responses simultaneously is provided below in Figure 21. For clarity, only the upper sideband response is shown in cases where the two are determined separately – as shown in the results above, the difference in response between the upper and lower sidebands in each measurement case is not important compared to the difference between measurement methods. As previously mentioned, the vertical position on the dB scale of the frequency response in each case is not relevant – a constant offset in dB units is equivalent to some constant gain (or attenuation) factor in linear units. Thus the differing response of the VNA and the heterodyne setup compared to the simulation data can be...
explained by the use of the EDFA to boost the signal for measurements, as well as frequency-independent losses such as coupling through adapters and fiber losses.

The important parameter in this case to describe the rolloff, is the proportionality constant describing the attenuation of the signal in logarithmic units (i.e. dB/decade). This corresponds to the exponent in a power law relationship. The analysis above focused on the determination of this fitting parameter, and the results are summarized in Table 2.

**Table 2: Summary of data fitting results.**

<table>
<thead>
<tr>
<th>Method</th>
<th>Lower Sideband (dB/dec)</th>
<th>Upper Sideband (dB/dec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Simulation</em></td>
<td>-53.25</td>
<td>-56.12</td>
</tr>
<tr>
<td><em>Heterodyne</em></td>
<td>-60.81</td>
<td>-65.51</td>
</tr>
<tr>
<td><em>VNA</em></td>
<td>-58.04 (-79.99 full span)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 21: Comparison of VCSEL response from modeling, heterodyning, and VNA.**
The experimental techniques show a faster rolloff than the simulation data. This is in accord with expectations; the simulation does not take into account the non-ideal nature of the rest of the elements in the experimental setup. It is noted that the rolloff for the VNA deviates dramatically from the other results if the entire frequency span is used in the linear fit. This suggests that a larger frequency range must be measured using the other two methods, to more fully evaluate the effectiveness of these techniques. However, if the analysis is restricted to the effective range of all three methods, then the results are very much in agreement.

One unexpected result is that for the two methods that differentiated between sidebands, the rolloff differed between the upper and lower sidebands. For a free-running VCSEL, it is expected that the response be symmetric. Examination of the data suggests that the difference is not attributed to random noise; the upper and lower sidebands in both cases differ systematically – this is supported by the fact that both methods show higher attenuation of the upper sideband as opposed to the lower.

Another metric that describes the shape of the frequency response of the system is the knee frequency – that is, where the response of the system drops to one half (-3 dB) of its initial value. The initial value of each response was found by fitting the first part of the response (that was discarded in the rolloff analysis) to a first-order polynomial and taking the constant term as the DC response value. The linear fit for each method was evaluated at regular points to find the frequency at which the response dropped to -3 dB of its initial value. These results are listed in Table 3.
Table 3: -3 dB knee frequency of response curves as measured by different methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Lower Sideband Knee</th>
<th>Upper Sideband Knee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>8.13 GHz</td>
<td>7.94 GHz</td>
</tr>
<tr>
<td>Heterodyne</td>
<td>11.48 GHz</td>
<td>8.70 GHz</td>
</tr>
<tr>
<td>VNA</td>
<td></td>
<td>8.13 GHz</td>
</tr>
</tbody>
</table>

With the exception of the lower sideband for the heterodyne measurement, the knee frequencies are in good agreement. It is thought that a poor fit for the passband of the heterodyned lower sideband caused an incorrect determination of the low-frequency baseline to which the -3 dB point is referred. Nevertheless, the good agreement of the rest of the figures suggests that the shape of the frequency response of the VCSEL is similar, as predicted by simulation and checked by the two measurement methods. In combination with the promising results of the analysis of the rolloff region, this suggests that with the exception of multiplicative, frequency-independent factors, the three responses correspond well.
3. Conclusions

A heterodyne detection system has been constructed to measure the modulation sideband frequency response of VCSELs. In parallel to this, simulation data for VCSELs under modulation was generated by numerically solving the semiconductor laser rate equations and applying Fourier analysis to the time-domain signals produced. Additionally, measurements of the VCSEL sideband modulation frequency response were made using a VNA, for comparison with and to evaluate the efficacy of the heterodyne measurement technique.

It was shown by the simulations that the VCSEL’s modulation sidebands have a rolloff of -53.25 and -56.12 dB/decade, respectively for the lower and upper sidebands. The VNA measurement did not distinguish between the upper and lower sidebands, and yielded a rolloff of -58.04 dB/decade. Using the heterodyne measurement techniques, the lower and upper sidebands were observed to have rolloffs of -60.81 and -65.51 dB/decade respectively. These numbers are in fairly good agreement; also of note is that the unexpected measured asymmetry between the upper and lower sidebands is present in both the simulation and heterodyne results. Furthermore, the locations of the -3 dB knee point were evaluated for each response curve and were found to be in fair agreement, with the exception of the lower sideband of the heterodyned signal for which the reference intensity was incorrectly determined.

It was therefore found that in the frequency range of the measurements (8-20 GHz), the heterodyne detection technique described in this report is an effective method to measure the frequency response of free-running VCSELs.
4. Recommendations

a) Investigate the use of time-averaging or the ‘max hold’ function on the RFSA during heterodyne measurements as it may allow more accurate determination of peak amplitudes. As all of the signal frequencies are either specified or known in the system, their position becomes unimportant and the temporal drift experienced by the signal can be safely ignored.

b) Develop methods to measure and analyze heterodyne data as well as simulated spectra to higher frequencies. It was noted earlier in the report that the VNA reported significantly different results when taking into account its entire frequency span. If the other methods can be extended to the higher-frequency range, the efficacy of these techniques could be more adequately evaluated.

c) Continue development of automated methods for data collection and analysis. Since spectral methods require substantial analysis individually, this will allow collection of data with higher frequency resolution.

d) Further characterize of the heterodyne system – for instance, a noise floor calculation to determine the fundamental dynamic range and resolution of the system.

e) As originally planned, perform frequency-response measurements on injection-locked VCSELs. Determine if the efficacy of this technique extends to general devices.

f) Construct the second heterodyne measurement setup mentioned in [6], and observe if time stability and robustness of system with respect to frequency drift are improved.
Acknowledgements

The authors wish to thank the Optoelectronics group in the Department of Electrical and Computer Engineering at the University of British Columbia, for the opportunity to work with this laboratory. In particular, Benham Faraji has been very helpful for solving myriad practical problems relating to the implementation of this heterodyne measurement scheme. Dr. Jon Nakane and the Engineering Physics Project Laboratory have been invaluable for resources, particularly with respect to project management and other logistical matters. Lastly, the authors wish to acknowledge project sponsor Dr. Lukas Chrostowski for fruitful discussions related to the theory and implementation of the project, as well as his seemingly endless patience with the various foibles that invariably arise in the experimental sciences, particularly when a group of undergraduates is loosed mercilessly in the laboratory.
A. Appendix: Description of Experiment Control Code

The following outlines the operation of the final version of rfsa.m, a copy of which is located in Z:\GROUP\LC\GROUP\Equipment\Agilent E4407B and ..\HP 70908B RFSA. A fully documented version of this code can be found in Appendix B.

The program begins by taking several inputs from the user – in order, it takes a filename to assign to the data files, the start and stop modulation frequency, and the interval size for the modulation sweep. For example, typing the command ‘rfsa(‘data’,3,5,0.1)’ would result in data being recorded for each modulation frequency between 3 and 5 GHz, at 0.1 GHz intervals, and would save the files under names beginning with ‘data’.

There are several constant values set in the start of the program. The most important value is that of ‘E4407’, which tells the program whether or not the RFSA being used is the Agilent E4407B (which corresponds to a value of ‘1’) or the HP 70900 (corresponds to a value of ‘0’); if the incorrect value is given, the program will not function properly. Other constants include the GPIB addresses for the RFSA (same value for either analyzer) and the signal generator.

The ‘E4407’ value is used in the next step of the program, where the device-specific commands are assigned to a number of string constants. These commands vary from setting the start frequency on the RFSA to reading the spectrum data, and are different for each analyzer. Aside from the commands sent to the analyzer, the code for the program is completely independent of the RFSA being used; however, if the incorrect commands are sent, the RFSA will not be able to interpret them. Each command is labeled with an appropriate string, but further information on their function can be found in the HP70800
Programming Manual and the Agilent E4401 Programming Reference, located in Z:\GROUP\LC_GROUP\Equipment\Equipment Manuals.

After setting up the GPIB objects MATLAB uses to communicate with different instruments, the program determines the number of iterations for which it will loop. If the user wants the program to iterate only a single time, they can input a value of ‘0’ for the modulation frequency interval. From this point onwards, every command in the script is executed for each loop.

The modulation frequency is determined based on current loop value and the inputs, and set on the signal generator. The sweep time of the RFSA is then read, to give the program a value of how long it should pause before actually recording measurement data (to ensure that at least one sweep of the spectrum has taken place). After this, the amplitude data for each point in the spectrum is downloaded from the RFSA.

Once it has downloaded the data for the full spectrum (which should contain, at the least, peaks corresponding to the carrier frequency and two sideband frequencies, as well as the modulation frequency), the script reads through the amplitude data to find the maximum intensity (ignoring the modulation frequency peak, and the noise common at very low frequencies); this value corresponds to the carrier frequency. This frequency is used to find the location of the upper and lower sidebands, as they can be found at the carrier frequency +/- the modulation frequency, respectively, as per the discussion in Section 2.1.2.

Having determined the position of the upper and lower sidebands, the script zooms in on each one (first the upper sideband and then the lower) by sending commands to the RFSA
to adjust the start and stop frequencies to values in closer proximity to the sideband peak. By zooming in on the sidebands, more data points in the actual peak can be recorded, which provides more useful data for analysis. Spectral data is recorded for both of the sidebands just as it was for the full spectrum.

At this point, the script has recorded all of the desired data (for a single iteration. The original settings of the RFSA are restored, to set it up for future sweeps of the full spectrum, and the data is formatted and saved into several data files, each containing two columns: the first contains the frequency points of the spectrum (in Hz) and the second contains the amplitude (in dBm) at each point. Three data files are saved, with names given by the inputted filename appended with the modulation frequency and a suffix – either ‘_fs.dat’, ‘_us.dat’ or ‘_ls.dat’ – based on whether it is data for the full spectrum, upper sideband or lower sideband (See Table 4). A graph is also displayed, showing each of the three recorded spectra. In addition, a data file is saved – appended with ‘_info.dat’ – which contains the useful information about the spectra taken (such as sweep time, and span frequencies). After this point, the program will loop again, if there are further iterations, else it will close off the GPIB objects as the final operation.

<table>
<thead>
<tr>
<th>Filename</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>data_3GHz_fs.dat</td>
<td>Full frequency spectrum</td>
</tr>
<tr>
<td>data_3GHz_us.dat</td>
<td>Upper sideband spectrum</td>
</tr>
<tr>
<td>data_3GHz.ls.dat</td>
<td>Lower sideband spectrum</td>
</tr>
<tr>
<td>data_3GHz_info.dat</td>
<td>RFSA settings</td>
</tr>
</tbody>
</table>

Table 4: Filename convention for heterodyne spectrum data
B. Appendix: Experiment Control Code

function r=rfsa(name,mod_freq_start,mod_freq_stop,mod_spacing);

%----- Download Spectra from Agilent E4407A, HP 70900B ----------
% Created by: Matthew von Schilling
% Last modified: March 23, 2007

% The program downloads three sets of spectral data for a given
% modulation frequency: it first sweeps the entire spectrum, and saves
% this data, then zooms in on the two sidebands (the positions of which
% are determined based on modulation frequency and the carrier
% frequency) and downloads the spectra for each sideband

% The program is designed to automatically measure spectra at each of
% the modulation frequencies in the span set by the user with the input;
% the program can be set to iterate a single time (at only the starting
% modulation frequency) by setting the modulation spacing to 0

% Either the Agilent E4407A or the HP 70900B RFSA can be used to
% download spectra, by setting the appropriate value at the start of
% the program

% This program also automatically sets the modulation frequency of the
% HP 83731 Signal Generator to the value input

% The program takes the following inputs (in order):
% - a string for the name of the file
% - the modulation frequency to start the span
% - the modulation frequency to stop
% - the interval spacing for the modulation frequency

% **Note: the program will use the original settings for the RFSA from
% the point the program operation is started (things such as
% video bandwidth, start and stop frequencies, sweep time, etc.)

%------------------------------------------------------------
% Gives the span over which to measure the zoomed sideband (in GHZ)
sideband_span = 2;

% GPIB address for the RFSA (default is 18 for both)
RFSA_ADDRESS = 18;

% GPIB address for the Signal Generator (default is 25)
SIGGEN_ADDRESS = 25;

% Set to 1 if using Agilent E4407, 0 if using HP70900B
E4407 = 1;

% Set to 1 to display graphs of the data at the end
DISPLAY_GRAPH = 1;

%------ Setting up program commands ----------
% Set the device specific strings used to send commands to the RFSA
if (E4407 == 1)
    read_sweep = 'SENSe:SWEep:TIME?;';
    read_videobw = 'SENSe:BANDwidth:VIDeo?;';
    read_resbw = 'SENSe:BANDwidth:RESolution?;';
    format_spectrum = 'FORMat:TRACe:DATA ASCii;';
    read_trace = 'TRACe:DATA? TRACE1;';
    read_start = 'SENSe:FREQuency:START?;';
    read_stop = 'SENSe:FREQuency:STOP?;';
    set_center_part = 'SENSe:FREQuency:CENTer';
    set_span_part = 'SENSe:FREQuency:SPAN';
    set_start_part = 'SENSe:FREQuency:START';
    set_stop_part = ':SENSe:FREQuency:STOP';
    set_freq_end = ';';
else
    read_sweep = 'ST?;';
    read_videobw = 'VB?;';
    read_resbw = 'RB?;';
    format_spectrum = 'TDF P;';
    read_trace = 'TRA?;';
    read_start = 'FA?;';
    read_stop = 'FB?;';
    set_center_part = strcat('CF',32)
    set_span_part = strcat('SP',32)
    set_start_part = strcat('FA',32)
    set_stop_part = strcat('FB',32)
    set_freq_end = 'HZ;';
end

% Sets strings for communicating with the Signal Generator
set_modulation_freq_part = 'SOURce:FREQuency:CW';
set_modulation_end = 'GHZ;';

%----- Setting up GPIB Objects ----------

% Creates the GPIB object for the RFSA
RFSA = gpib('agilent',7,RFSA_ADDRESS);
set(RFSA,'InputBufferSize',90000);
buffer=get(RFSA,'InputBufferSize');

fopen(RFSA);
clrdevice(RFSA);

% Creates the GPIB object for the Signal Generator
SIGGEN = gpib('agilent',7,SIGGEN_ADDRESS);
set(SIGGEN,'InputBufferSize',90000);
buffer=get(SIGGEN,'InputBufferSize');

fopen(SIGGEN);
clrdevice(SIGGEN);

% If the modulation interval is set to zero, the program will only loop
% a single time, at the start frequency input
if (mod_spacing <= 0)
    iterations = 0;
else
    iterations = (mod_freq_stop - mod_freq_start)/mod_spacing;
for i = 0:iterations,
    mod_freq = mod_freq_start + mod_spacing*i;
    fprintf(SIGGEN,strcat(set_modulation_freq_part,num2str(mod_freq), set_modulation_end));
end

%----- Downloading the first trace -------

% Reads sweep time, to set the time to wait before measuring
sweep_time = fscanf(RFSA,'%f');
fs_sweep = sweep_time;
wait_time = sweep_time + 2;
pause(wait_time);

% Reads in some information to be stored as reference in a data file
video_bw = fscanf(RFSA,'%f');
res_bw = fscanf(RFSA,'%f');

% Reading the trace data
ampl = fscanf(RFSA,'%s');

% Read span data, in order to assign frequency data points
start = fscanf(RFSA,'%f');
fs_start = start;
stop = fscanf(RFSA,'%f');
fs_stop = stop;

ampl = str2num(ampl)';
freq = linspace(start*1e-9,stop*1e-9,length(ampl))';

% This code looks through the spectrum on both sides of the modulation frequency, so as to avoid the possibility of misidentifying the modulation peak as the VCSEL peak
% This does not alter the actual spectrum data
modulation_pos = ((mod_freq*1e9 - start)*(length(ampl)/(stop-start)));
modulation_pos = round(modulation_pos) + 1;

% Function: determine maximum value in array, C gives value, I gives position
% Use to find the maximum amplitude value in the array (the carrier % frequency) and find the corresponding frequency
% Uses carrier to determine the position of the sidebands
[C,I] = max(ampl(20:(modulation_pos - 2)));
possible_max = C;
[C,I] = max(ampl((modulation_pos + 2):length(ampl)));
if (C > possible_max)
    C;
else
    C = possible_max;
end
peak_index = find(ampl == C);
% Absolute value on lower sideband since a negative frequency on account of large modulation frequency will display the sideband at the positive frequency (of same amplitude)
center_lower = abs(freq(peak_index) - mod_freq);
center_upper = freq(peak_index) + mod_freq;

%-------- Download Sideband Traces --------
% Setting the string commands for changing the frequency span
warning off MATLAB:deblank:NonStringInput;
center_lower_string = strcat(set_center_part,32,num2str(center_lower*1e9),set_freq_end);
center_upper_string = strcat(set_center_part,32,num2str(center_upper*1e9),set_freq_end);
span_string = strcat(set_span_part,32,num2str(sideband_span*1e9),set_freq_end);
warning on MATLAB:deblank:NonStringInput;

%-------- Download the Lower Sideband --------
fprintf(RFSA,center_lower_string);
fprintf(RFSA,span_string);
% Clears input, which must be done in between measuring trace data
flushinput(RFSA);

fprintf(RFSA,read_sweep);
sweep_time = fscanf(RFSA,'%f');
ls_sweep = sweep_time;
wait_time = sweep_time + 2;
pause(wait_time);

fprintf(RFSA,read_trace);
ampl_lower = fscanf(RFSA,'%s');

fprintf(RFSA,read_start);
start = fscanf(RFSA,'%f');
ls_start = start;
fprintf(RFSA,read_stop);
stop = fscanf(RFSA,'%f');
s_stop = stop;

ampl_lower = str2num(ampl_lower)';
freq_lower = linspace(start*1e-9,stop*1e-9,length(ampl_lower))';

%-------- Download the Upper Sideband ---------
fprintf(RFSA,center_upper_string);
fprintf(RFSA,span_string);
flushinput(RFSA);

fprintf(RFSA,read_sweep);
sweep_time = fscanf(RFSA,'%f');
us_sweep = sweep_time;
wait_time = sweep_time + 2;
pause(wait_time);

fprintf(RFSA,read_trace);
ampl_upper = fscanf(RFSA,'%s');

fprintf(RFSA,read_start);
start = fscanf(RFSA,'%f');
us_start = start;
fprintf(RFSA,read_stop);
stop = fscanf(RFSA,'%f');
us_stop = stop;

ampl_upper = str2num(ampl_upper)';
freq_upper = linspace(start*1e-9,stop*1e-9,length(ampl_upper))';

%-------- Restore Original Settings ---------
% Restores the settings on the RFSA that were present at the start
% of the measurement

warning off MATLAB:deblank:NonStringInput;
start_string =
    strcat(set_start_part,32,num2str(fs_start),set_freq_end);
stop_string =
    strcat(set_stop_part,32,num2str(fs_stop),set_freq_end);
warning on MATLAB:deblank:NonStringInput;

fprintf(RFSA,start_string);
fprintf(RFSA,stop_string);

%----- Format and Save the Data, and Plot -------
% Three data files are saved: one for the original spectrum, one
% for the lower sideband and one for the upper sideband (labeled
% '_fs' for full spectrum, '_ls' for lower sideband, and '_us' for
% upper sideband)

filename=strcat(name,'_',num2str(mod_freq),'GHz');
dlmwrite(strcat(filename,'_fs.dat'),[freq
    ampl],'delimiter','\t','precision','%.6f','newline','pc');
ret1 = dlmread(strcat(filename,'_fs.dat'));
plot(freq,ret1(:,2));
%saveas(gcf, strcat(filename,'_fs'),'fig');

dlmwrite(strcat(filename,'_ls.dat'),[freq_lower
    ampl_lower],'delimiter','\t','precision','%.6f','newline','pc');
ret2 = dlmread(strcat(filename,'_ls.dat'));
plot(freq_lower,ret2(:,2));
%saveas(gcf, strcat(filename,'_ls'),'fig');

dlmwrite(strcat(filename,'_us.dat'),[freq_upper
    ampl_upper],'delimiter','\t','precision','%.6f','newline','pc');
ret3 = dlmread(strcat(filename,'_us.dat'));
plot(freq_upper,ret3(:,2));
%saveas(gcf, strcat(filename,'_us'),'fig');

% Creating a plot to show all three measured spectra at once
if(DISPLAY_GRAPH == 1)
    subplot(3,1,1); plot(freq,ret1(:,2))
    subplot(3,1,2); plot(freq_lower,ret2(:,2))
    subplot(3,1,3); plot(freq_upper,ret3(:,2))
end

%---- Creating an information file containing data about spectra --
% Another data file is created (labeled '_info') which contains
% information about the RFSA settings while measurements were being
% taken

id = fopen(strcat(filename,'_info.dat'),'wt');
warning off MATLAB:deblank:NonStringInput;
s1 = strcat('Spectrum analyzer settings for',filename);
s2 = '';
s3 = 'Full Spectrum:';
s4 = strcat('Start frequency =',num2str(fs_start/1e9),'GHz');
s5 = strcat('Stop frequency =',num2str(fs_stop/1e9),'GHz');
s6 = strcat('Sweep time =',num2str(fs_sweep),'s');
s7 = strcat('Video Bandwidth =',num2str(video_bw),'Hz');
s8 = strcat('Resolution Bandwidth =',num2str(res_bw),'Hz');
s9 = 'Lower Sideband:';
s10 = strcat('Start frequency =',num2str(ls_start/1e9),'GHz');
s11 = strcat('Stop frequency =',num2str(ls_stop/1e9),'GHz');
s12 = strcat('Sweep time =',num2str(ls_sweep),'s');
s13 = 'Upper Sideband:';
s14 = strcat('Start frequency =',num2str(us_start/1e9),'GHz');
s15 = strcat('Stop frequency =',num2str(us_stop/1e9),'GHz');
s16 = strcat('Sweep time =',num2str(us_sweep),'s');
warning on MATLAB:deblank:NonStringInput;
fprintf(id,'%s
',s1,s2,s3,s4,s5,s6,s7,s8,s9,s10,s11,s12,s2,
    s13,s14, s15,s16);
fclose(id);

fprintf('Data collection complete
');

45
%----- Close off the GPIB objects ------------

fclose(RFSA);
delete(RFSA);
clear RFSA;

fclose(SIGGEN);
delete(SIGGEN);
clear SIGGEN;
C. Appendix: VCSEL Alignment Procedure

C.1 Equipment List

- VCSEL with mounting fixture for optical stage
- optic fiber patch cord with mounting fixture for optical stage
- three optical stages as described in text
- IR card
- ruler graded in mm or finer divisions
- optical power meter, e.g. Agilent 8163A lightwave multimeter with HP 81525A optical head
- bias current supply for VCSEL, e.g. Keithley 2602 Sourcemeter (tunable VCSELs require one voltage-regulated supply and one current-regulated supply)
- laser with fiber-coupled output, e.g. HP 8164A
- optical breadboard
- mounting post
- mounting clamps for fixing VCSEL leads
- cap screws for mounting stages and clamps to breadboard

For coupling the VCSEL's output into optic fiber, two lenses are used, one to collimate the light from the VCSEL and one to focus the collimated light into the fiber. The VCSEL, lenses, and fiber are mounted on three adjustable stages, as on Figure 22. Call the horizontal axes x and y and the vertical axis z, and let the VCSEL emit light along the x-axis. Then the VCSEL position is adjustable along the z axis, the position of the lenses is adjustable in the y and z axes, and the position of the fiber is adjustable in all three axes.
C.2 **Coarse Collimation and Alignment of VCSEL**

The coarse adjustment of collimation and alignment of the lens stage with the VCSEL can be done visually using an IR card to observe the output of the VCSEL.

- Mount the stages to the breadboard. Mount the VCSEL to its stage and mount one of the lenses to the lens stage at the end of the track nearest to the VCSEL. Mounting the VCSEL with accurate angular alignment appears to be critical, as a VCSEL mounted on a long circuit board had coupling losses 12dB greater than a VCSEL mounted on a shorter, more rigid circuit board or to a socket in a massive mounting block.

- Install the mounting post about one metre away from the lens, so that the output of the VCSEL will strike the post when it is collimated and aligned along the x axis. Note the location on the post here the beam from the VCSEL should strike.
• Turn out the lights in the lab. Apply bias current and voltage to the VCSEL. Use the IR card to find the light emitted by the VCSEL. The IR card will show a red spot where the IR emitted by the VCSEL strikes it. Move the card along the x-axis to find the path of the beam. Adjust the VCSEL stage x knob to make the beam the same width all the way along its length. Adjust the lens stage y and z knobs to align the beam along the x axis – that is, make the beam strike the mounting post at the desired location.

• Illuminating the apparatus with blue light (as from a cell phone LCD backlight) or low-intensity white light (such as spill around the edges of the blackout curtains) can make it easier to see the apparatus while still allowing you to see the red spot on the IR card.

• Sometimes it is helpful to, with the lights on, put the corner of the IR card’s active area where you want to aim the beam from the VCSEL. When the lights are off, you will not be able to see the IR card, but you will be able to see the sharp edge when the beam reaches the corner of the card.

**C.3 Coarse Alignment of Fiber**

Like the alignment of the lens stage with the VCSEL, the coarse alignment of the fiber with the VCSEL-lens system can be done visually with an IR card. Aligning the spot from the VCSEL with the end of the fiber is difficult; it is easier to use an auxiliary laser to send light backward through the system, and focus the spot from the auxiliary laser on the VCSEL.
• Once the beam is collimated and aligned along the x axis, shut off the VCSEL bias supplies and install the second lens and the fiber on their respective stages. Connect the other end of the fiber to the output of the HP 8164A. Set the 8164A for the lowest output power that will make a visible spot on the IR card. With the IR card used when writing this procedure, -13dBm (the lowest setting available) was adequate.

• Hold the corner of the IR card in front of the opening in the VCSEL can. Use the fiber stage x knob to focus the light from the 8164 to a spot at approximately the x-position of the VCSEL and use the y and z knobs to align the spot with the opening in the VCSEL can. You may need to move the VCSEL away from the lenses to make room for the IR card. If so, note the original position of the VCSEL on the micrometer scale and restore it later.

**C.4 Fine Alignment**

The fine adjustment of the alignment depends on observing power gradients using the power meter. The goal is to find the setting for each of the six knobs that maximizes the power coupled to the power meter. Unfortunately, it is not sufficient to adjust each knob in turn separately, because the power-maximizing setting for each knob depends on the setting of the other knob corresponding to that axis, and only one combination of settings will give overall maximum power. One can visualize the power function for any particular axis as a three-dimensional surface, with power plotted as the vertical dimension and the settings of the two relevant knobs as the horizontal dimensions (Figure 23). Holding the position of one knob constant and adjusting the other while observing the reading on the power meter is equivalent to cutting a thin slice of the surface. By
comparing the maxima of adjacent slices, it is possible to determine the two-dimensional direction of the power gradient and follow the gradient to find a maximum.

![Diagram of power coupled vs VCSEL stage x position and Fibre stage x position](image)

**Figure 23: Hypothetical function relating power in fiber and x-positions of stages.**

- Turn off the 8164A laser. Disconnect the fiber from the laser and connect it to the power meter. Note the reading on the power meter when no power is applied to the VCSEL. Bias the VCSEL and observe the new reading on the power meter. If the power detected by the power meter does not increase when the VCSEL is turned on, the rough alignment was not accurate enough.

- Assuming that the power coupled from the VCSEL into the power meter is detectable, arbitrarily choose an axis to adjust first, and then choose one knob to sweep and one to adjust in steps. If one knob moves more smoothly than the other, sweep the smooth one.

- Adjust the swept knob in one direction, watching for the measured power to increase to a maximum. If the power definitely only decreases (say, falls to 10dB...
below the initial level or falls below the noise floor of the power meter), reverse the direction of adjustment and continue searching. Note that the micrometer screws generally have some hysteresis or backlash, so that the stage position corresponding to a given knob setting depends on the direction in which the stage is travelling. Therefore, it is best to switch directions in a region distant from any suspected maximum, lest the maximum is skipped past. At this time, it is not important to note the position of the swept knob corresponding to the power maximum, only the power. This is the maximum power for the first slice.

- Now adjust the stepped knob to select a different slice. A difference in maximum powers may be measurable for steps as close as 0.03 mm (0.001 in) apart. Repeat the sweeping procedure for each step, and note whether the maxima are increasing or decreasing; if they are decreasing, step in the other direction. To maintain a consistent position reference after the direction change, despite the hysteresis of the stepped-knob screw, take up the backlash by turning the knob past the original mark in the new (reverse) direction, then turning it in the original direction to the original mark.

- Once the slice with the maximum power for a given axis is found, set the swept and stepped knobs accordingly and move on to the next axis. Once all three axes are adjusted, repeat the alignment procedure, beginning with the first axis, to check that no further improvement is possible. Coupling losses as low as 7dB have been achieved with TO-56 packaged VCSELs by this procedure.
function [f,P] = spec(T, Y)
% spec(Y,T) plots the power spectrum of specified time-domain signal
% with values Y at times T. For unequally-spaced times, spec will
% perform cubic spline interpolation. Written by Matt Lam
%(lamm@interchange.ubc.ca)
% Feb/Mar 2007

% OPTION FLAGS
INTERP = 0;
% END OPTION FLAGS

N=length(T);
T=T(:)';
Y=Y(:)';
Y=Y-mean(Y); %remove DC offset

%Generate interpolated time/space values
totaltime=max(T)-min(T);

switch INTERP
  case 0
    t=T;
    y=Y;
  case 1
    t=linspace(min(T),(max(T)),length(T));
    y=interp1(T,Y,t,'spline');
  case 2
    t=min(T)+([0:N-1]/(N))*(max(T)-min(T))';
    y=interp1(T,Y,t,'spline');
end

%take the fft (power spectrum)
p= fft(y);
unique = ceil((length(y)+1)/2);
p=abs(p(1:unique))*2;
p(1)=p(1)/2; % Account for endpoint uniqueness
p(length(p))=p(length(p))/2;
p=p/(length(p)); %normalize
%scale the frequency and plot answer
freq= ([0:unique-1]/totaltime);
semilogy(freq,p);
S = [freq' p''];
f=freq';
P=p';
return;
function [t,E]=imp(fname,carrier)
%imports .field simulation data and creates vectors denoting time, and
%electric field E=sqrt(pd).*exp(i*((phase)-(2*pi*carrier*t))).

%OPTION FLAGS
WINDOW=1; %window the e-field

a=dlmread(fname);
t=a(:,1);
t=t.*(1e-9); %convert time to nanoseconds
pd=a(:,2);
phase=a(:,3);
E=sqrt(pd).*exp(i*((phase)-(2*pi*carrier*t))); %compute electric field
if(WINDOW)
    w=blackman(length(E));
    E=E.*w;
end
return;
function params=specfit(f,p,car,mod)
%FITTING Create plot of datasets and fits
% FITTING(F,P) Creates a plot, similar to the plot in the main curve fitting window, using the data that you provide as input. You can apply this function to the same data you used with cftool or with different data. You may want to edit the function to customize the code and this help message.
% CODE GENERATED BY MATLAB CF TOOLBOX AND MODIFIED BY MATT LAM 29 MARCH 2007

% Set up figure to receive datasets and fits
f_ = clf;
figure(f_);
legh_ = []; legt_ = {}; % handles and text for legend
xlim_ = [Inf -Inf]; % limits of x axis
ax_ = subplot(1,1,1);
set(ax_,'Box','on'); hold on;

%--- Plot data originally in dataset "p vs. f"
f = f(:);
p = p(:);
h_ = line(f,p,'Parent',ax_,'Colour',[0.333333 0 0.666667],...
       'LineStyle','none', 'LineWidth',1,...
       'Marker','.', 'MarkerSize',12);
xlim_(1) = min(xlim_(1),min(f));
xlim_(2) = max(xlim_(2),max(f));
legh_(end+1) = h_;
legt_{end+1} = 'p vs. f';

%Nudge axis limits beyond data limits
if all(isfinite(xlim_))
xlim_ = xlim_ + [-1 1] * 0.01 * diff(xlim_);
set(ax_,'XLim',xlim_);
end

% --- Create fit "fit 1"
fo_ = fitoptions('method','NonlinearLeastSquares','Lower',[-Inf -Inf 0 -Inf -Inf -Inf -Inf -Inf -Inf 0]);
%st_ = [521.3144830768 16293929712.46 629439865.3912 8.592653793918 car-mod 1244939659.376 8.283416707982 car+mod 1045148456.114 ];
st_ = [521.3144830768 16293929712.46-mod 1244939659.376 8.283416707982 car+mod 1045148456.114 ];
set(fo_,'Startpoint',st_);
ft_ = fittype('gauss3' );

% Fit this model using new data
cf_ = fit(f,p,ft_ ,fo_);

% Or use coefficients from the original fit:
if 0
cv_ = {528.0051855867, 16276815488.06, 429680613.1069, 8.820360890383, 10277490477.62, 429514460.7245, 8.723812587946, 22275312333.91, 427516563.9796};

cf_ = cfit(ft_, cv_{:});
end

% Plot this fit
h_ = plot(cf_, 'fit', 0.95);
legend off; % turn off legend from plot method call
set(h_(1), 'Colour', [1 0 0],...
    'LineStyle', '-', 'LineWidth', 2, ...
    'Marker', 'none', 'MarkerSize', 6);
legh_(end+1) = h_(1);
legt_(end+1) = 'fit 1';

hold off;
legend(ax_, legh_, legt_);
params = coeffvalues(cf_);
return;
function r=prn2dat(filename);
%
%----- Convert PRN File to DAT File ----------
% Created by: Matthew von Schilling
% Last modified: March 15, 2007
%
% This program converts PRN files, which are created when S-Parameter
% data is saved on the Agilent Network Analyzer, to basic DAT files
%
% The data is preserved in the conversion, with frequency (in Hz) in
% the first column and the S-Parameter magnitude (in dB) in the second
% column; the headers and commas are removed from the PRN file,
% allowing easier use of data in analysis
%
% The original PRN file is kept, and a new DAT file is created with the
% same name

prninput = textread(filename,'%s','headerlines',2);

% Loop to split the data into separate columns
j = 1;
h = 2;
for i = 1:801
    freq(i) = prninput(j);
magn(i) = prninput(h);
j = j + 2;
h = h + 2;
end

freq = freq';
magn = magn';

% Loop to remove the commas from each value
for i = 1:801
    freq(i) = strrep(freq(i),',','');
magn(i) = strrep(magn(i),',','');
end

% Convert from string values to numeric values
freq = str2double(freq);
magn = str2double(magn);

% Saving the new data in a DAT file
filename = strrep(filename,'.prn','.dat');
dlmwrite(filename,[freq magn],'delimiter','\t','precision','%d','newline','pc');
clear;
E. Appendix: Characterization of TO-56 Pin Package VCSELs

This information was collected over the course of attempts to conduct heterodyne frequency response measurements on TO-56 package VCSELs after the failure of the VCSELs that were originally to be studied. It is presented here for the convenience of future students and researchers. To find these VCSELs in the lab, first find the black antistatic box marked with the desired wafer ID, then find the receptacle inside the box with the desired VCSEL number.

The pinout for all of these devices is as shown in Figure 24 below. For the VCSELs characterized in Table 5 below, 1304 nm devices are not tunable and the tuning pin is apparently open circuited. 1550 nm VCSELs require a tuning voltage applied to the tuning pin, positive with respect to the ground pin, in order to operate.

![Figure 24: Pinout of TO-56 package VCSELs.](image)
Table 5: Characterization of VCSELs in TO-56 packages

<table>
<thead>
<tr>
<th>Wafer ID</th>
<th>VCSEL no.</th>
<th>Wavelength (nm)</th>
<th>Tuning voltage for maximum optical power (V)</th>
<th>Maximum optical power (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B03-136Q</td>
<td>037</td>
<td>1304</td>
<td>n/a</td>
<td>unknown</td>
</tr>
<tr>
<td>B03-136Q</td>
<td>039</td>
<td>1304</td>
<td>n/a</td>
<td>unknown</td>
</tr>
<tr>
<td>B03-136Q</td>
<td>044</td>
<td>1304</td>
<td>n/a</td>
<td>no output</td>
</tr>
<tr>
<td>B03-136Q</td>
<td>049</td>
<td>1304</td>
<td>n/a</td>
<td>unknown</td>
</tr>
<tr>
<td>B03-136T</td>
<td>828</td>
<td>1304</td>
<td>n/a</td>
<td>unknown</td>
</tr>
<tr>
<td>B03-136H</td>
<td>639</td>
<td>1304</td>
<td>n/a</td>
<td>unknown</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>762</td>
<td>1550</td>
<td>25.3</td>
<td>-10.39</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>763</td>
<td>1550</td>
<td>11.0</td>
<td>-14</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>766</td>
<td>1550</td>
<td>14.0</td>
<td>-26.52</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>768</td>
<td>1550</td>
<td>19.2</td>
<td>-10.10</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>770</td>
<td>1550</td>
<td>23.2</td>
<td>-9.13</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>771</td>
<td>1550</td>
<td>12.7</td>
<td>-11.6</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>773</td>
<td>1550</td>
<td>23.0</td>
<td>-9.21</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>774</td>
<td>1550</td>
<td>19.5</td>
<td>-9.93</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>775</td>
<td>1550</td>
<td>20.8</td>
<td>-10.64</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>777</td>
<td>1550</td>
<td>20.1</td>
<td>-5.91</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>778</td>
<td>1550</td>
<td>16.7</td>
<td>9.02</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>779</td>
<td>1550</td>
<td>0.0</td>
<td>-9.96</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>780</td>
<td>1550</td>
<td>21.5</td>
<td>-6.89</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>781</td>
<td>1550</td>
<td>17.0</td>
<td>-8.21</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>782</td>
<td>1550</td>
<td>11.7</td>
<td>-7.44</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>783</td>
<td>1550</td>
<td>7.3</td>
<td>-10.02</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>784</td>
<td>1550</td>
<td>12.1</td>
<td>-7.63</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>785</td>
<td>1550</td>
<td>12.0</td>
<td>-7.95</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>786</td>
<td>1550</td>
<td>18.8</td>
<td>8.36</td>
</tr>
<tr>
<td>F02-057, F01-155B</td>
<td>787</td>
<td>1550</td>
<td>13.8</td>
<td>-7.35</td>
</tr>
</tbody>
</table>

For all of the VCSELs listed above, bias current was set at 5 mA. Typical voltage drop across the VCSELs was 2.5 V.
F. Appendix: Project Self-Evaluation

As stated in the project proposal, the original intention for this project was to measure the frequency response of injection-locked VCSELs using two heterodyne measurement setups [6]. The objectives of the project were twofold: First, to determine the behaviour of the modulation sidebands under injection locking, and second, to observe differences in the performance of the two heterodyne systems. A cursory comparison of this report with the contents of the project proposal shows significant deviation between the intended scope and goals of the project, and actual results. Most notable were two significant changes:

- The experiments were conducted on free-running VCSELs rather than with optical injection locking,

- The second heterodyne measurement apparatus was not constructed.

Early in the course of the project, it was found that an implementation and characterization of the measurement method would be of more use than a speedy set of measurements. Therefore, the length of time intended for free-running experiments was lengthened at the expense of adding injection locking. With the unexpected failure of the VCSEL under test close to the project deadline, it was no longer feasible to order more from the European production facilities as outlined in the proposal. The project sponsor had more VCSELs available, but these devices were of a different pin configuration, and thus necessitated new hardware for mounting and interfacing. While the coupling on the previous devices to a detector was accomplished by a fiber probe automatically positioned by a piezoelectric element, the new pin package necessitated coupling
manually via a set of micrometer dials. In the end it was deemed that time constraints precluded continued tests with the new VCSELs.

The failure of the VCSEL also prevented further testing based on the results of the first experiments, the results of which were outlined in the rest of this report. Accordingly, many of the refinements and modifications that were intended for later experiments have been suggested in the Recommendations section for future implementation.

The MATLAB control software ended up being much more extensive than originally planned, as concern over the Agilent E4407B RFSA being borrowed midway through the project and issues with the HP 70900B RFSA not accepting some GPIB commands necessitated that the program be modular enough to communicate with either RFSA.

These repeated hardware problems necessitated the extension of the first two milestone dates. With this adjustment, these milestones were met on time. With the obliteration of the VCSEL under test, it was impossible to meet the third milestone as proposed. Consultation with the Project Lab resulted in a rethinking of the project scope and goals, which is reflected in this Recommendation Report. Though the authors were unable to accomplish their stated goal of investigation of sideband asymmetries in injection-locked VCSELs, the adjusted project milestones were met on time. Close communication with the project sponsor as well as the Project Lab were essential to nimble reworking of the objectives and goals of this project.
References


Bibliography


