Final Report on VECSEL Optimization: VIGRE Summer 2007

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1 Introduction

Vertical External Cavity Surface Emitting Lasers (*VECSELs*) are a type of laser that have been found to be useful in situations requiring high output power and pulses of short duration. The typical VECSEL is composed of (at least) two mirrors: the *active* or *gain mirror* where the light is amplified and reflected and an outcoupling mirror where some laser light is allowed to exit the laser. When one desires to create laser pulses rather than a continuous beam a third mirror is added, known as the passive mirror or *SESAM* (SEmiconductor Saturable Absorber Mirror). The design of the VECSEL with the SESAM is of particular interest due to its ability to deliver both very rapid (on the order of GHz) and high power (typically on the order of milli-Watts) pulses. Within the VECSEL these three mirrors are situated in a "V" shaped cavity, with the gain mirror occupying the lower portion of the "V" and the SESAM and outcoupling mirror situated at the other two ends—as it travels through the VECSEL, a pulse is reflected off the active mirror, the SESAM, and again off the gain mirror before returning to outcoupling mirror again [1] [5]. For the purposes of this paper, our focus will primarily on the active mirror and secondarily on the SESAM.

Both the active and passive mirrors have a similar structure composed of two principle parts: the *Distributed Bragg Reflector* (DBR) and the Quantum Well Stack (there is only one quantum well in the SESAM, while there are multiple in the active mirror). The DBR is a periodic structure of reflective interfaces that cause the incoming light to be gradually reflected as it travels through the mirror, creating a very high quality reflector (often with reflectivity of more than 99.9% [6]) [4]. A constant percentage of the light is transmitted at each interface in the DBR, thus causing the intensity of the incoming light to decay exponentially as it travels into the DBR, and grow exponentially as it leaves. A representation of the DBR can be seen in Figure 1, where the DBR occupies the right side of the structure. The quantum well stack is the portion of the mirror that allows for increases in the power of the pulse, causing the *Resonant Periodic Gain* (RPG) through the presence of the quantum wells. The quantum well stack is a structure somewhat similar to the DBR, with the obvious difference being that it contains quantum wells. The gain on each pass through the quantum well stack is small, so many loops through the mirror are required to create a high-power laser pulse. See Figure 1 for a representation of the quantum well stack and the growth of the incoming light pulse as it travels through it.

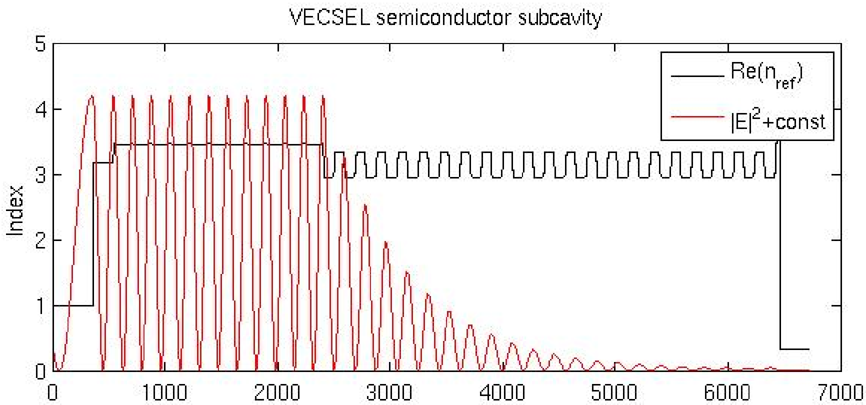


Figure 1: Structure of the active mirror in a VECSEL, showing the DBR (the periodic structure on the right) and the quantum well stack (in the left half of the image). Notice that the incoming light wave is intensified slightly as it moves through the quantum well stack, and decreases exponentially as it goes deeper into the DBR.

Each of these components (the DBR in both the active mirror and SESAM, and the RPG structure in the active mirror) can be modified by applying various *chirps* to the structure. A chirp describes how the frequency or period of some oscillating structure changes with time. The period of the DBR determines what wavelengths of light the mirror will reflect by causing the reflected light to interfere constructively or destructively with the incoming light–when the DBR is "tuned" to certain frequencies of light, the amplitude of the incoming and reflected waves will coincide, causing them to be stronger, while the amplitudes of other frequencies will not coincide and will become weaker. This feature of the DBR can be exploited by applying a chirp to the mirror. By changing the chirp of the mirror, one can vary the "depth" into the mirror that each wavelength of light penetrates, and thus the amount of time each wavelength spends within the mirror. Through the manipulation of these delays one can change the properties, such as the shape, of the pulse itself. In particular, the first part of this research project involves the creation of linear chirps—when the frequency or period changes linearly in space. Linear chirps will be applied to all components of the VECSEL in this portion of the project.

Upon completion of this initial phase of the project, we consider only the DBR in the active mirror and allow it to take on an arbitrary chirp using a genetic algorithm-based optimization method.

1.1 The Problem

Currently, the active mirror in the VECSEL creates nonlinear distortions in both the phase and amplitude of the pulse. The goal of this project is to modify the mirrors in the VECSEL to compensate for these distortions. More specifically, this project seeks to find a way to modify the active and/or passive mirrors so as to create a short, bandwidth-limited (having a flat spectral phase) pulse [3].

1.2 Research Plan

The research for this project consisted of two phases. The first phase of the project was be directed towards gaining an understanding of how the pulse is affected by each component of the VECSEL, beginning with the DBR on the active mirror in isolation and progressing to added complexity. The second phase concentrated on applying optimization algorithms to generate solutions to the problem of nonlinear distortions.

2 Linear Chirps on the Mirror

My investigation of the VECSEL began by considering only the DBR in the active mirror component of the laser. The DBR was chosen to be examined first due to its relatively simple nature and the possibility that changing the DBR by itself might provide enough control to solve the eventual optimization problem. The investigation of the DBR would also provide a sound basis for later changing the RPG structure with fairly little change required between the two programs.

2.1 Linear Chirps on the DBR

Initial testing consists of generating a series of linear chirps on the DBR (and later on other components) and observing the effects on the reflectivity of the mirror as a function of the wavelength of the incoming light. For this initial test it was elected that a constant length would be used to modify each layer, since the two principle layers were of similar lengths (82.83 and 71.8 nm), while leaving the ramp layers unaffected (2.0 nm each). Specifically, the linear chirp formula used is:

$$Layer\ Thickness = L + \frac{i - 10}{10}\delta$$

where L is the original length of the layer, δ is the desired difference between the length of the original layer and the outer layers, i an index corresponding to current layer, $i = 0, 1, \ldots, 20$ (for the 21 layers of the DBR), and the number 10 was chosen to ensure that the length of the center layer was preserved.

To evaluate the changes in the mirror structure, plots of the reflectivity were examined. Figure 2 illustrates the reflectivity (squared amplitude) as well as real and imaginary components over the entire computed frequency range for this mirror.

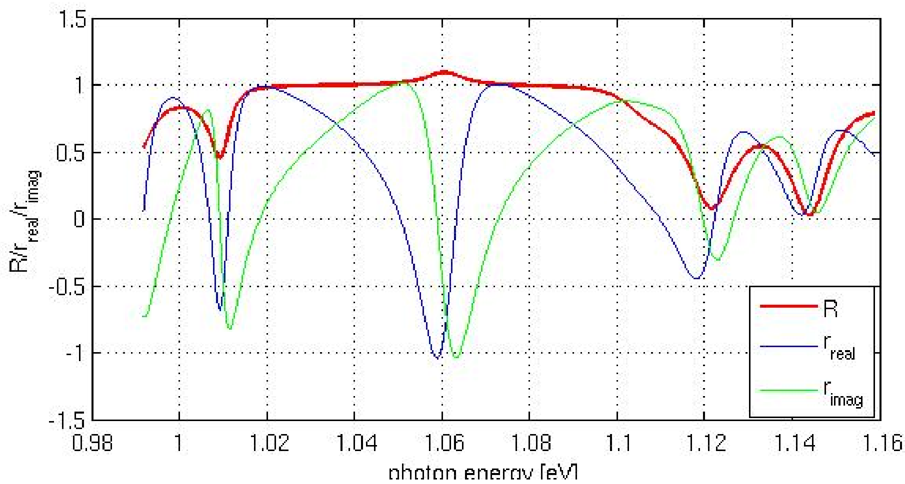
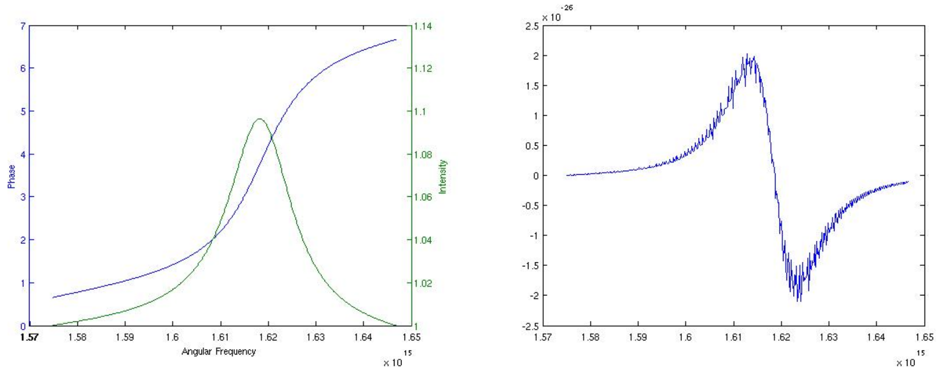


Figure 2: Reflectivity over the entire computed frequency range

We are principally interested in the gain peak—the area where the reflectivity exceeds unity and the pulse is thus amplified. Figure 3(a) shows the amplitude and phase of the reflectivity in the region of the gain peak. Note that the gain peaks at nearly 10% and that the concavity of the phase reaches zero near the peak of the gain, as illustrated by the numerical 2nd derivative plot in Figure 3(b).

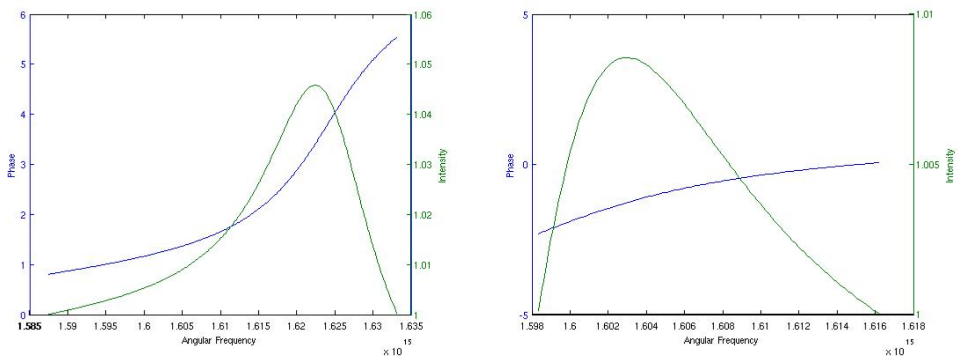


(a) Amplitude and Phase around the gain peak

(b) Second derivative of the phase

Figure 3: Properties of the active mirror around the gain peak

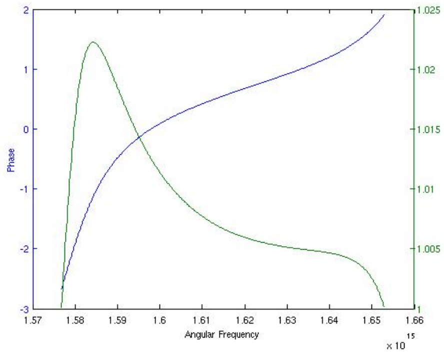
By experiment, it was determined that a range of δ of $[-9, 5]$ would allow for the existence of a gain peak with no other changes to the mirror. Changing the chirp of the DBR had the principle effect of shifting the position of the gain peak and shape of the phase plot, as well as lowering the gain, as illustrated in Figure 4. Notice also that the shape of the peak is somewhat modified by the change in chirp.



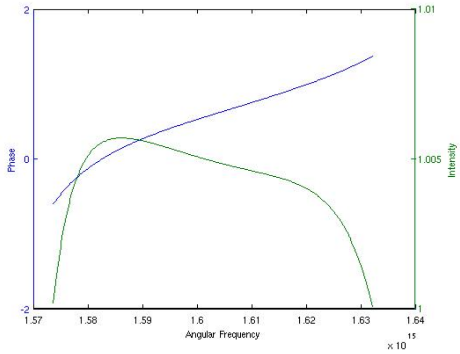
(a) DBR chirp of 2.5

(b) DBR chirp of -9

Figure 4: Examples of the effects of chirping on the DBR



(a) RPG: -20%, DBR: -5



(b) RPG: 20%, DBR: 2

Figure 5: Examples of the effects of chirping both the DBR and the RPG structure

2.2 Linear Chirps on the RPG

A linear chirp generator for the RPG was added and the two were tested together. Because the spacing layers around the quantum wells had a much more drastic difference between their lengths (10 and 142.3 nm), a percentage based chirp system was adopted. The formula used in this case was:

$$Layer\ Thickness = L\left(1 + \frac{i-(N-1)/2}{N/2}\delta\right)$$

where L, i and δ are defined as above, N is the total number or repetitions in the quantum well stack, and $i = 0, 1, \ldots, N-1$. Again, this formula was designed to ensure that the length of the center layers would remain constant. Experiments seem to indicate that there is relatively little restriction on the range of the linear chirp of the RPG structure for $[-100, 100]\%$, provided that the DBR chirp is selected so that it provides a gain peak by itself.

Combining the two chirps allowed for more drastic changes to the shape of the gain peak, but still had the effect of lowering the gain. Some examples are given in Figure 5.

2.3 Changing Buffers

In this VECSEL design, there are buffers on either side of the RPG structure that can also be changed to alter the reflectivity of the laser. In the original structure, both of these buffers have a length of 146.12 nm. However, by changing the front buffer to 60.12 nm, we can change the reflectivity of Figure 5(b) (RPG: 20%, DBR: 2) to that in Figure 6. Note that although the gain peak increased from just over 0.5% to nearly 6%, it did not return to the height of the original (10%). This feature may indicate that changing the buffers can allow for an extension of the usable region for the chirp. The question of whether buffers can be selected to increase the gain back to the original height has not been determined.

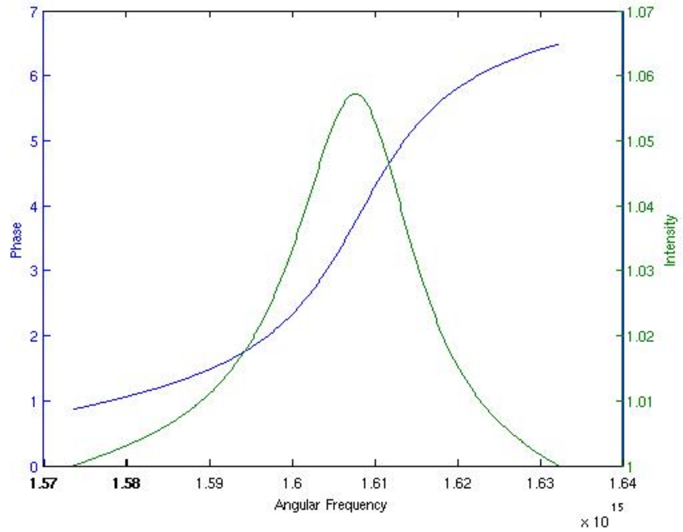


Figure 6: Example of the effect of modify the buffers

3 Pulse Propagation

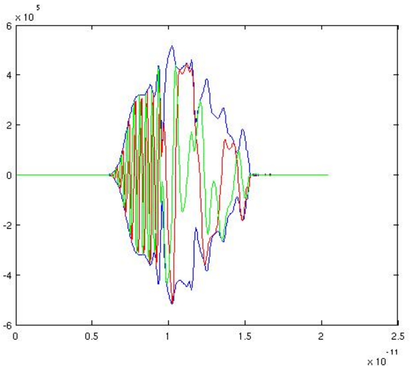
In order to better determine how changing the mirror properties on both the active and passive mirrors will affect the laser pulse generated a one-dimensional code for simulating the propagation of a laser pulse through a VECSEL was developed at the ACMS. I have constructed interfaces between this code and the linear chirp generators to examine the effect of changing the mirrors on the pulse.

This phase of the project included an extra mirror, the SESAM. Because of this, a different set of reference mirrors were used in the linear chirp generators.

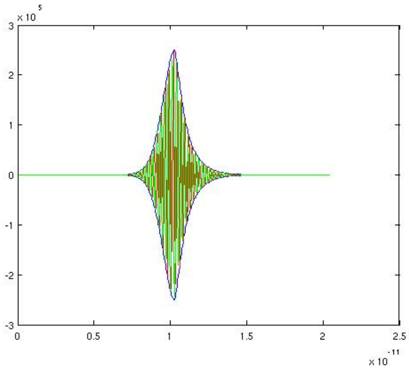
By altering the three input parameters (the linear chirps for the RPG and DBR on the active mirror, and the DBR on the SESAM), a variety of output pulses have been found though manual searches. Some of the pulses have been noisy, which would have no counterparts in real experiments, such as in Figure 7(a).

Others can been seen as a composition of several individual pulses that can move relative to each other over time, such as the pulse depicted in Figure 7 between 30,000 (7(c)) and 50,000 (7(d)).

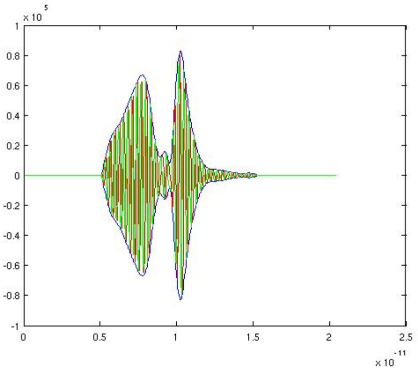
However, there has been some success in finding stable and well shaped pulses. One of the best examples that has been found by hand thus far is in Figure 7(b), which has chirps of 4%, 2% and -8% for the SESAM, DBR and RPG, respectively, although similar pulses exist in the region surrounding this point. Other examples of well shaped pulses have been found in other chirp regions.



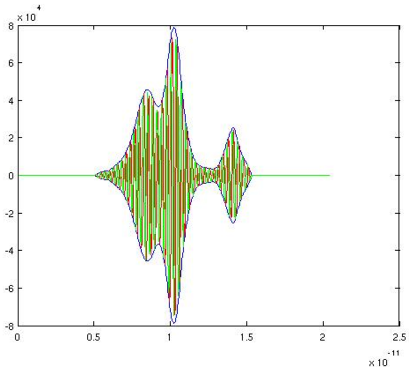
(a) Example of a poor pulse



(b) An example of a well shaped pulse



(c) Composition of pulses after 30,000 iterations



(d) Composition of pulses after 50,000 iterations

Figure 7: A composition of pulses as it is reflected through the cavity

4 Optimization

Upon completion of the initial period of testing and becoming familiar with the nature of the problem work on the optimization routine could begin. It was apparent at this time that the approach taken in the initial phase of applying linear chirps to the mirror would not be sufficient for the goal of producing a short, high-power bandwidth-limited pulse. For this we would need to take a much broader approach including more general shapes. For this portion of the project, the focus was placed once again on the DBR in the active mirror, so as to reduce the number of parameters needed it describe the general shapes.

In order to allow for the creation of general shapes, a new 25 parameter model was constructed. In this new model, each of the DBR's 25 periods was allowed to change width independently of the other layers, growing or shrinking up to 30% in either direction. The 30% limit was enforced for practical reasons, i.e., allowing layers to become too small may cause the lasers to be impossible or impractical to create physically.

4.1 Genetic Algorithm

A genetic algorithm approach was chosen for the undertaking of the actual optimization for the project. The genetic algorithm was chosen because it is an approach that has had success in many other large-scale optimization problems, as well as the easy availability of no-cost software on the internet and the impracticality of using gradient-based approaches (due to the lack of an analytical form of the gradient). The software for this work used the GAlib genetic algorithm package, written by Matthew Wall at the Massachusetts Institute of Technology [7].

The genetic algorithm is an optimization technique inspired by the phenomenon of biological evolution. Each genetic algorithm is initialized with a number of (usually randomly selected) candidate solutions, referred to as individuals or, collectively, as the population. The optimization proceeds in discrete units called generations. During the course of each generation all individuals in the population are evaluated with the objective function and given a corresponding fitness value. The objective function is the function that is to be either maximized or minimized. The fitness function transforms the objective function value into something immediately usable by the genetic algorithm. In some situations the fitness function can be as simple as an identity or a linear scaling of the objective function value, although it may be more complicated in other cases.

The transition between generations is accomplished by means of the evolution-inspired methods of mutation and crossover. The crossover operations describes how "children" are created through the union of (usually) two parents, while the mutation operation describes how to stochastically change a single individual. Both methods are defined to suit the problem at hand, but there are several common strategies in their implementation. For example, the mutation could involve randomly changing the value of one or more of the parameters in an individual, or randomly switching the values of two of the parameters. Crossover operations typically involve swapping portions of the solution between the two parents to create the children, e.g., creating one child with parameters 1-13 from the first parent, 14-25 from the second, and vice versa with the second child. Much more information on crossover and mutation operations can be found in [2] and on the GAlib website [7].

This project primarily utilized the swap crossover and a mutation function consisting of creating small perturbations in all variables. The objective function was taken as a linear combination of the width of the pulse measured at $\frac{1}{10}$ of the maximum height and a standard deviation of the frequency of the carrier in the pulse. This objective function was to be minimized in order to achieve the goal of finding a narrow, bandwidth limited pulse.

5 Results

Results from the implementation of the genetic algorithm were immediately seen to be much more promising than the initially taken route of linear chirps. Large improvements in both the width and bandwidth of the pulse were found nearly immediately upon full implementation of the genetic algorithm. Examples of the improvements found are given in figures 8(a) and 8(b) (with the pulse generated by the reference mirrors included in 8(c)). For larger images see Figure 10 in the appendix.

Unfortunately, the structure of these solution mirrors seem to display a high degree of oscillatory behavior or randomness, as seen in figures 9(a) and 9(b).

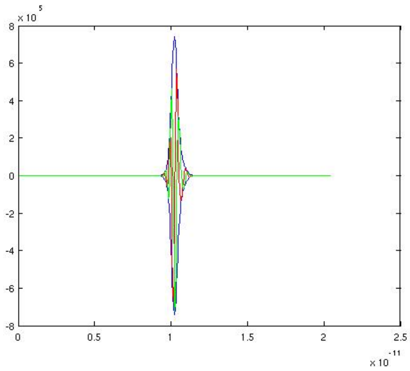
5.1 Stability

In order for the results of this study to be useful in improving the quality of manufactured VECSELs, the results must have some degree of stability. Unlike the computer simulations discussed in this report, the process of growing the mirrors for placement inside the VECSEL is not perfect. Errors in the growing process, both random and systematic, can influence the results. As such, the growing process must be as robust as possible towards such difficulties.

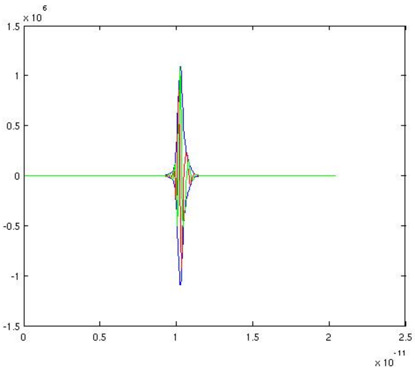
Unfortunately, the results of this project have not shown such robustness to date. Often, even relatively small changes in the solution structure will cause dramatic changes in the corresponding pulse. The sensitivity of the results seems to be especially troublesome when attempting changes that will modify the larger structure of the mirror—such as when attempting to flatten out peaks or troughs.

5.2 Optimization Stability

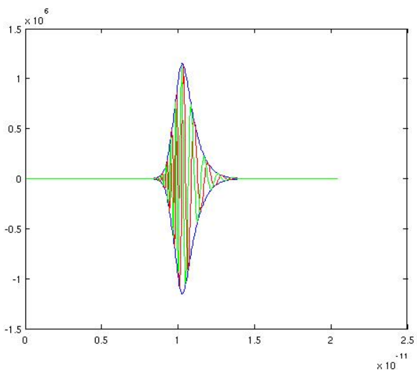
The genetic algorithm itself has also shown itself to be very sensitive to the initial population distribution. No perturbation tests have yet returned to the initial solution, some such tests have even resulted in returning worse solutions than the original. However, the genetic algorithm has a multitude of parameters and methods that can be changed to create different behavior. Within this variety there may be a combination that is well suited to checking for areas of convergence of the optimization. However, it is evident that this test is incompatible with the methods used for a full search of the solution



(a) 475 fs pulse



(b) 379 fs pulse



(c) Pulse generated by reference mirrors, 1.38 ps

Figure 8: Well shaped pulses found with the GA.

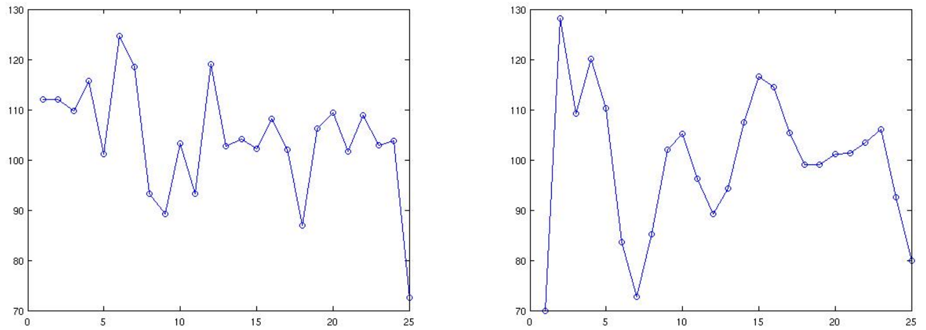
space.

6 Conclusion

A genetic algorithm-based optimization routine was selected to determine the optimal design for the DBR to produce a narrow, bandwidth-limited pulse. By allowing each layer within the DBR to be scaled independently of each other, a full range of possible shapes for the structure of the mirror was created, rather than limiting the optimization to only the generation of linear slopes as was the case in the initial stages of the project. Upon full implementation of the GAlib library with the simulation code already created, positive results began to be found immediately.

Unfortunately, to date the stability results of both the solutions found and of the genetic algorithm itself have been lacking. It is often the case that seemingly small changes to the structure of the DBR can cause dramatic (and almost universally disadvantageous) changes to the resulting pulse. If the results of this study are to be implemented in the manufacture of VECSELs the results must be robust to both systematic and random changes in the structure of the laser. Further research must be done to determine both the nature and severity of these instabilities, and to the question of whether any corrective actions can be taken.

The optimization algorithm itself also shows high degree of sensitivity



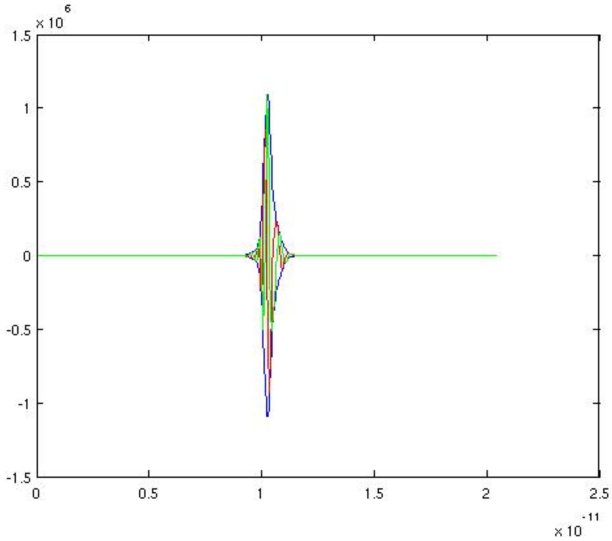
(a) Figure 8(a) structure

(b) Figure 8(b) structure

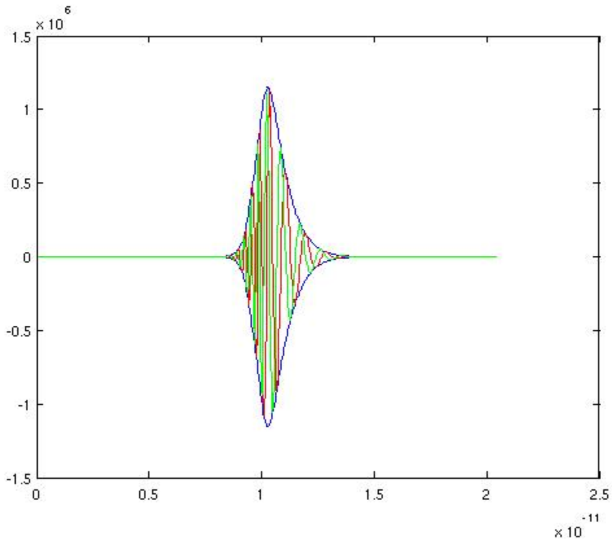
Figure 9: DBR structures found by the genetic algorithm. Each point entrepreneurs a multiplier (expressed as a percentage) of the original length of the DBR found in the reference mirror. For example, a value of 120 would indicate that the layer is 20% larger than the original layer in the reference mirror.

with respect to the initial population. Even relatively small perturbations are unlikely to return to the initial solution, and may even find solutions with less optimal objective function scores, and no two separate runs of the optimization program have returned the same results to date. It may be possible, however, that the form that the genetic algorithm must take will vary substantially between that of searching the entire function space and searching only a small local area. More work needs to be done to determine and quantify these differences for this optimization problem. We must also work to quantify the sensitivity of mirror structures and corresponding pulses with respect to the perturbations that are likely to be seen in the manufacturing process, and to develop methods for finding mirrors that are insensitive to such manufacturing errors.

A Comparison of Initial Pulse and GA Results



(a) 379 fs pulse from 8(b)



(b) Pulse generated by reference mirrors, 1.38 ps fs

Figure 10: Comparison of initial pulse (b) and pulse after optimization (a).

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