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AN OVERVIEW OF LASER OPERATION AND MODELOCKING OF A VERTICAL EXTERNAL CAVITY SURFACE EMITTING LASER (VECSEL) SYSTEM

BY

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THESIS

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ABSTRACT

VECSEL laser systems are important additions to the family of lasers. They exhibit a combination of desirable lasing features that are usually not simultaneously attainable. These features are high power, diffraction limited beam quality, intra-cavity frequency doubling, tunability, and ultrashort pulses generated from passive mode-locking. In this work, we give a brief overview of the VECSEL structure, previous VECSEL literature, how lasing in a VECSEL works, and how mode locking in a VECSEL works.

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Thanks be to Yahweh who gives me the victory

CHAPTER 1

INTRODUCTION

1.1. Background

Before the advent of the laser, optics existed primarily in the realm of geometrical and

classical optics. Despite many advances in lens design, microscopes, telescopes,

cameras, and objectives; there were limitations: Classical light sources were woefully

incoherent (a limit fundamental to the available sources), were severely limited in output

power, and were not sufficient as amplitude-and-frequency-stabilized single wavelength

sources.   These problems were solved by the laser. But first what is coherence?

There are two primary types of coherence: temporal coherence (or coherence time) and

spatial coherence. Temporal coherence is a measure of the phase relationship of the same

point on a wave train at two instances in time. As defined in [VLE], it is "the net delay

that can be inserted in a wave train and still obtain interference". Another interpretation

is how long the phase retains a "memory" of the value it had at an earlier time [KFO].

Temporal coherence can be approximated by $\tau_c \approx \frac{1}{\Delta v}$ where Δv is the bandwidth of the

medium [KFO]. Typical values for everyday sources are only on the order of tens of

milliseconds; typical values for lasers can range from nanoseconds for common

laboratory lasers to trillions of nanoseconds for the most stable [PIO].

Spatial coherence (or longitudinal coherence length) is a measure of the phase

relationship between two points along a wave train. It is given by $l_t = c\tau_c$. Typical

values for everyday sources are a few wavelengths; typical values for lasers range from

meters to several kilometers [PIO]. Next are power considerations.

Typical light sources are limited in power output. Natural light sources can give off up to a few kilowatts. Continuous-wave laser output can range from a few mW to an order of a Watt in a laboratory, to several MW or greater for military applications. Some experiments can reach powers on the order of 10^{20-22} Watts. Pulsed lasers tend to operate on the order of 10^{15} Watts, though only for a few picoseconds or less [SL].

Typical light sources are noisy, that is, exhibit jitter in amplitude and phase (frequency). Lasers are stable and can exhibit nearly ideal single frequency characteristics. This is primarily an effect of the cavity more so than the characteristics of the medium [SL]. There also exist external methods, both optical and electrical, that are used to stabilize the amplitude and/or phase of a laser system.

Lasers have also brought about many other advances, after first being touted as: "A solution looking for a problem". Nowadays, lasers are ubiquitous in both pure science research and applied science/engineering. They have revolutionized spectroscopy, through their nearly single frequency stabilization, opened up the field of quantum optics, through phase concerns, have enabled the study of nonlinear optics, and have enabled the creation of new states of matter (Bose Einstein Condensates, Fermionic Condensates, supersolids, etc). They are used every day in fiber optic communications, for fundamental experiments in quantum physics, are used to define metrology standards, and are considered promising for the detection of gravitational waves. But what exactly is the laser?

1.2. What is a LASER?

LASER stands for <u>L</u>ight <u>A</u>mplification by <u>S</u>timulated <u>E</u>mission of <u>R</u>adiation. In short, the laser is a device that provides gain and resonant feedback to electromagnetic radiation. Through the use of an external pumping source, radiators in the gain medium are excited. After some time, they de-excite and emit photons (light). As the light traverses the cavity, the gain medium is still being pumped. When the first emitted light comes back into the gain medium, stimulated emission occurs, causing the light to be amplified. This occurs for frequencies of light that match the overlap resonances of the cavity and the gain medium.

1.3. Common laser systems

There are many types of laser systems: the Ruby laser (the first known laser), rare-earth lasers, dye lasers, gaseous-discharge lasers (the most developed), excimer lasers, free electron lasers, diode (semiconductor) lasers (currently the most important), and thin disk lasers. He-Ne gas-discharge lasers are known for their very good beam quality. Semiconductor lasers are known for good spectral coverage and, in certain cases, low divergence/diffraction limited output [THEC]. Thin disk lasers have power outputs in the kW range [WTHS].

1.4. Vertical External Cavity Surface Emitting Lasers (VECSELs)

A VECSEL combines the best elements of the previous laser types: low divergence/diffraction limited output, output in W or more, compact, "rugged" visible sources, and some of the shortest pulses achievable in laser systems. They are solid state

lasers made up of a combination of a semiconductor quantum well gain medium pumped by a diode laser [THEC], but closely resembling disk lasers. They are distinct from most solid state lasers in that the waveguide gain path is built perpendicular to the junction as opposed to parallel to it.
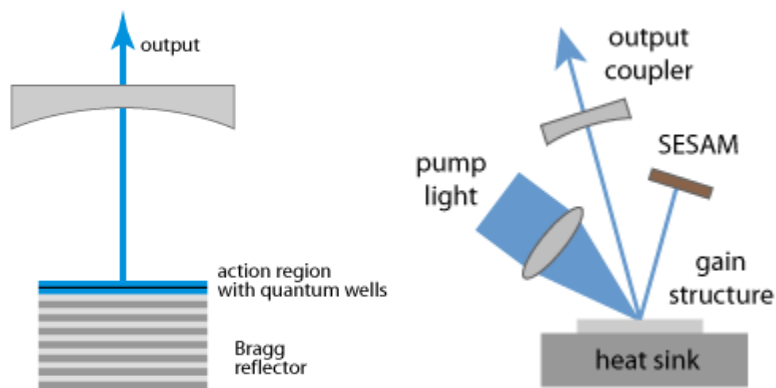

Fig 1. Typical VECSEL system and typical cavity setup for modelocking. Source: [RPVX]

1.4.1. Semiconductor quantum well gain medium (laser cavity)

Quantum wells are thin layer materials used to confine particles (in this case, radiators) in the dimension parallel to the laser output. They are two dimensional gain media (as opposed to one dimensional quantum wires and zero dimensional quantum dots) exhibiting quantum confinement. They are formed from mismatches in the bandgaps of neighboring semiconductor materials in a double heterostructure formation. These radiators see a lower energy in the center layer, hence a potential well [MOPQ]. We know from quantum mechanics, that particles in a quantum well have a discrete set of energies. Exciting an electron raises it to a higher bound state, separating it from a hole. When it recombines with a hole, it gives off radiation. These bound state energies are called the sub-bands of the well. In this thesis, multiple quantum wells will be

considered in distinction to superlattices. The distinction being that there is no significant penetration of the electron wavefunction into nearby quantum wells. We also assume: all transitions in the quantum well have equal strength, an infinite quantum well, and in-plane dispersion [QWWD]. In these cases, quantum mechanics dominates: the number of allowed transitions in any given energy interval (joint density of states) and the band structure of the medium [MOPQ].
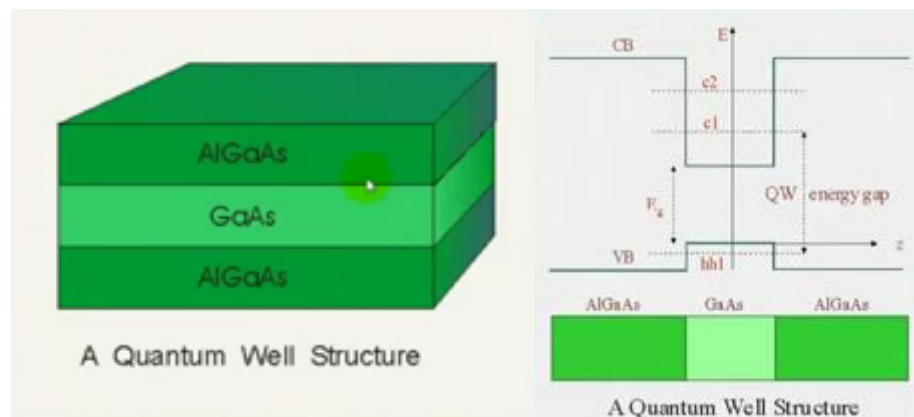

Fig 2. Typical heterostructure and resulting quantum well. Source: [WIVL]

1.4.2. Quantum Confinement and Density of States

Quantum confinement is essentially the change of electrical and optical properties of a material when its dimensionality is restricted. The new structure must also be near the semiclassical Bohr radius before quantum effects dominate. When this happens, the confined dimension gives rise to quantization of the charge carriers in that dimension. This leads to bound states in one or more dimensions. One-dimensional confinement leads to a well, two-dimensional leads to a wire, and three-dimensional leads to a dot. The width, depth, and even shape of the well are determined by growth, fabrication, and compositional grading of the materials making your structure [RTQC]. The shape of the

dispersion curves in both the conduction and valence bands are approximately given by

parabolic curves, with contribution from in-plane momenta [QWWD]:

$$E = \frac{\pi^2 n^2 \hbar^2}{2mL_\perp^2} + \frac{\hbar^2 |\mathbf{k}_{x,y}|^2}{2m^*} \qquad (1.4.2.1)$$

Where *m, m** are the conduction band electron mass and valence band effective hole

mass, respectively. The momentum of the well $k_{x,y}$ is an integer function of the width of

the well $L_\perp$ such that:

$$k_{x,y} = n \frac{2\pi}{L_\perp}. \qquad (1.4.2.2)$$

The momentum contribution of incoming photons is negligible to the system so that all

transitions are essentially vertical in the band gap [MOPQ]. For n bound states in the

sub-band, the density of states at any given energy is the sum over all sub-bands below it.

The result is a sum over step functions up to N_l subband levels [WTHS, RTQC, QWWD]:

$$\rho(E) = \frac{m^*}{\pi \hbar^2} \sum_{n=0}^{N_l} step(E - E_i). \qquad (1.4.2.3)$$

The total number of carriers in a given subband is given by [QWWD],

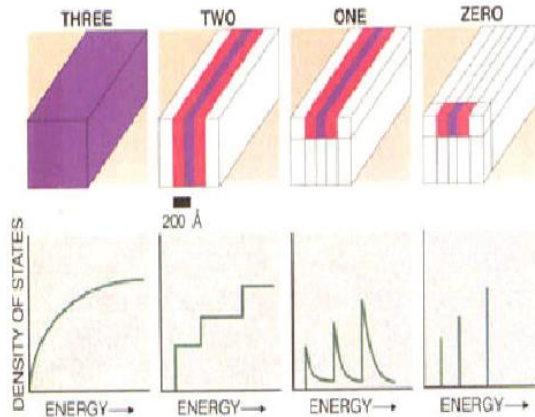$$N_{tot_{SUBBAND}} = \int_{SUBBAND} Pr^{f-d}(E)\rho(E)dE. \qquad (1.4.2.4)$$

Fig 3. Density of States for various dimensions. Source: [WTHS]

1.4.3. Distributed Bragg Reflectors and Gain

Distributed Bragg Reflectors are structures consisting of an alternating array of two differing optical materials. The most common version is the quarter-wave mirror where each layer thickness (at normal incidence) is one-quarter of the operating wavelength. Each interface of the differing materials yields a Fresnel reflection. All reflections from each interface interfere constructively for two reasons: the optical path length difference between reflections is half of a wavelength and the reflection coefficients for the interfaces have alternating signs. Therefore, constructive interference is present, yielding strong reflectivity. The reflectivity of this mirror setup is tuned by the number of layer pairs and the refractive index difference between layers [RPBM]. The structure is fabricated so that the quantum wells are located at the wave antinodes, yielding a maximum electric field [WTHS].
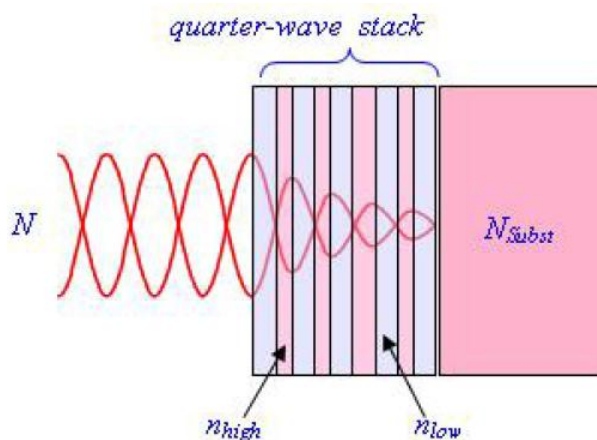

Fig 4. Distributed Bragg Reflector. Source: [WTHS]

The total gain of a VECSEL system is from both the quantum well material gain g and the intensity Γ_z of the electric field over the wells. The quantum well gives gain when the rate of stimulated emission is greater than the rate of stimulated absorption. In traditional optics parlance, gain occurs when $B_{21} > B_{12}$. This means the total gain is given by:

$$\text{Gain} = g\Gamma_z. \tag{1.4.3.1}$$

From this simple relation, we see that increasing the intensity increases the gain of the

sample, through an increase in the quantum well-laser coupling i.e. the resonance of this

microcavity system [WTHS]. For the necessary gain, the threshold carrier density

condition is [SDL]:

$$N_{th} = N_0 (R_1 R_2 T_{loss})^{-(2\Gamma g_0 N_w L_w)^{-1}}. \tag{1.4.3.2}$$

From reference [WHPP], we need a beam spot of 60 microns or less to achieve

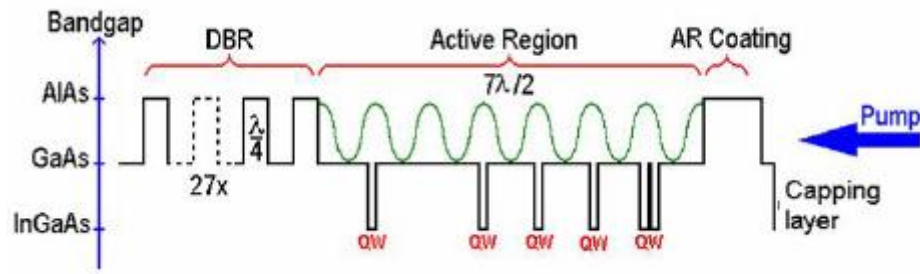modelocking, with a power of 200 to 300 mW, corresponding to 7.41 to 11.11 $\frac{kW}{cm^2}$.

Fig 5. Typical VECSEL gain medium. Notice quantum wells located at antinodes of E field standing wave, to maximize gain. Source: [WTHS]

CHAPTER 2

BEAM PROFILE ANALYSIS

2.1. Cavity considerations and the paraxial geometrical optics approximation

If we consider a ray of light as traveling parallel and nearly on-axis, it can be described

by two variables: r, the distance from the axis and α, the angle of incidence. This

approximation is useful for physical dimensions significantly greater than the wavelength

of light [WGO]. We can then combine these two variables into a 2 x 1 vector and

simultaneously describe any optical element (or combination of elements) by a 2 x 2

matrix [VLE, KFO, PIO]:

$$\begin{pmatrix} r_{final} \\ \alpha_{final} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r_{initial} \\ \alpha_{initial} \end{pmatrix},$$ (2.1.1)

where $AD - BC = \frac{n_2}{n_1}$. Matrices for some optical elements are as follows: translation:

$T_d = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$, refraction: $R_R = \begin{pmatrix} 1 & 0 \\ \frac{n_1 - n_2}{R n_2} & \frac{n_1}{n_2} \end{pmatrix}$, thin-lens:

$T_L = \begin{pmatrix} 1 & 0 \\ -\left[\frac{1}{\pm f} = \frac{n_2 - n_1}{n_1}\left(\frac{1}{R_1} - \frac{1}{R_2}\right)\right] & 1 \end{pmatrix}$, reflection from a spherical mirror: $R_L = \begin{pmatrix} 1 & 0 \\ \frac{2}{\pm R} & 1 \end{pmatrix}$,

where for both thin lens and reflection matrices, convex is (+) and concave is (-). The

free-space propagation length is d, $n_{1,2}$ are the index of refraction for medium 1 or 2, R is

the radius of curvature of a lens, and f is the focus of a lens. Propagation of a ray through

an optical system is accomplished by multiplying each matrix from each successive

optical element. Because each matrix must operate on the vector in order, the matrices

are listed in the reverse order, i.e. the 1st physical element is represented by the nth matrix,

the 2nd physical element is represented by the n-1st element and so forth. An example

follows, where the distance from the fiber pump to the first lens is set at the focal length
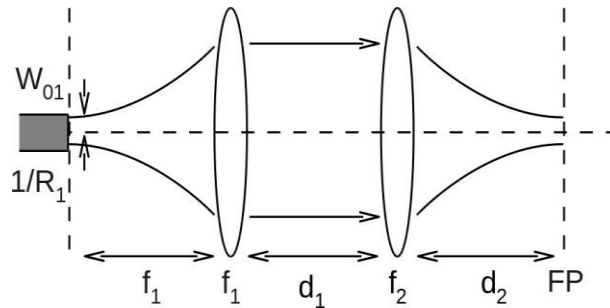
of this lens.

Fig 6. Lens system used to focus pump laser onto VECSEL medium.

The intuitive sequence for this is as follows: translation $1 (T_{d1})$, thin-lens $1 (T_{L1})$,

translation 2 (T_{d2}), thin-lens 2 (T_{L2}), and then translation 3 (T_{d3}). But since each

progression must operate on (i.e. change) the initial state we write:

$$\begin{pmatrix} r_{final} \\ \alpha_{final} \end{pmatrix} = T_{R3}T_{L2}T_{R2}T_{L1}T_{R1} \begin{pmatrix} r_{initial} \\ \alpha_{initial} \end{pmatrix}. \tag{2.1.2}$$

The result gives an example identical to (2.1.1). This result can be extended to any type

of optical system, even optical cavities [VLE]. If we replace the lenses with mirrors, we

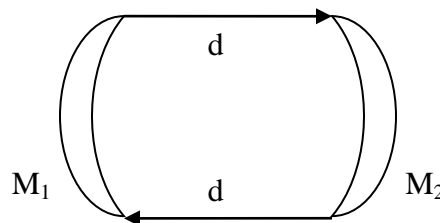get a very simple example of an optical cavity (generalized, not actual laser system used):

Fig 7. Diagram of a simple optical cavity with distance d and mirrors M_i

Following the previous example, the operator combination yields a four term sequence

that is the unit cell for this cavity:

$$\begin{pmatrix} r_{final} \\ \alpha_{final} \end{pmatrix} = R_{R2}T_{d2}R_{R1}T_{d1}\begin{pmatrix} r_{initial} \\ \alpha_{initial} \end{pmatrix}. \tag{2.1.3}$$

This equation as before, reduces to (2.1.1) as well. It is also known [VLE, SL,WGO] that

the condition for a stable cavity (that is a cavity that will keep all rays inside of itself) is:

$$0 \le \frac{A+D+2}{4} \le 1. \tag{2.1.4}$$

Expanding the center term in terms of the physical variables yields a simple relation in

terms of the stability g parameters:

$$0 \le g_1g_2 \le 1, \tag{2.1.5}$$

$$g_i = 1 - \frac{d}{R_i}. \tag{2.1.6}$$

This relation yields the simple but intuitive graph of g_2 vs g_1 (the stability diagram for
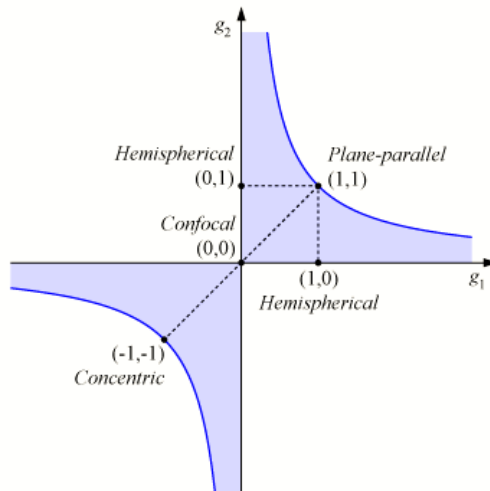
any 2 mirror cavity):

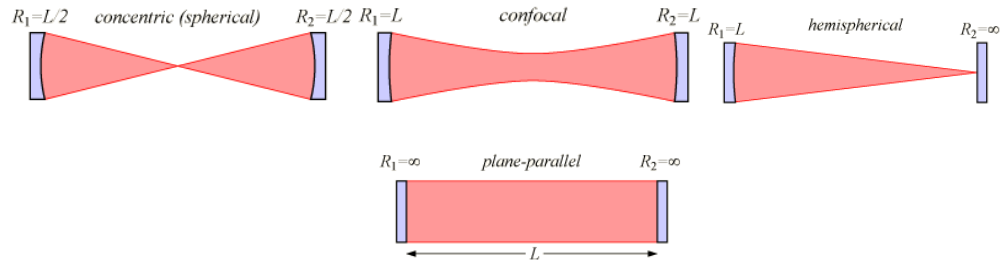Fig 8. Stability Diagram for various cavity types. Source: [WOC2]

Fig 9. Cavity types. Here, *L* equals *d* of previous developments. Our particular laser setup uses a type of ring configuration. Source: [WOC]

2.2. Gaussian theory and beam propagation in the paraxial wave approximation

Since light is an electromagnetic wave, we can describe its behavior with a wave equation. We assume propagation in a uniform medium such as air or vacuum. The resulting paraxial wave equation is (see Appendix):

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + 2ik\frac{\partial U}{\partial z} = 0. \tag{2.2.1}$$

U is an electric field with a currently unknown form, and k is the wavevector of light. We can also assume the form of our unknown field is symmetric in x and y (radially symmetric). Therefore, the resulting equation is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right) + 2ik\frac{\partial U}{\partial z} = 0 \tag{2.2.2}$$

After substituting in a form for U [VLE]:

$$U = e^{\left\{i\left[P(z) + \frac{kr^2}{2q(z)}\right]\right\}}, \tag{2.2.3}$$

and some phase arguments, we can arrive at an important equation using the complex beam parameter, *q* in terms of the wavelength, λ_0, radius of curvature, *R(z),* and index of refraction, *n* [VLO, SL, WGO, OUP]:

$$\frac{1}{q} = \frac{1}{R(z)} - i\frac{\lambda_0}{\pi n w_0^2(z)} \equiv a - ib. \tag{2.2.4}$$

From this we can calculate the radius of the minimum spot size anywhere along the beam:

$$w_0 = \sqrt{\frac{\lambda_0}{n\pi}b},$$ (2.2.5)

The inverse of the radius of curvature, $Re(\frac{1}{q})$:

$$a = \frac{1}{R(z)},$$ (2.2.6)

For the wavefront curvature at some distance z:

$$R(z) = z\left[1 + \left(\frac{\pi n w_0^2}{\lambda z}\right)^2\right],$$ (2.2.7)

And the Rayleigh range:

$$z_R = \frac{n\pi w_0^2}{\lambda_0}.$$ (2.2.8)

Any successive q-parameter along any point in the optical system can also be calculated using the matrices from earlier, with m as a normalization constant [WRTM]:

$$\begin{pmatrix} q_{1+i} \\ 1 \end{pmatrix} = m \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} q_1 \\ 1 \end{pmatrix}$$ (2.2.9)

This yields two equations that we divide to get [WRTM]:

$$\frac{1}{q_{1+i}} = \frac{C + \frac{D}{q_1}}{A + \frac{B}{q_1}}.$$ (2.2.10)

The location of the beam spot is found from propagating the ray according to ABCD matrices, and then finding the z value that gives:

$$Re\left(\frac{1}{q_{1+i}}\right) = 0,$$ (2.2.11)

Then, (2.2.5) can be used to find the actual beam waist at this location, where:
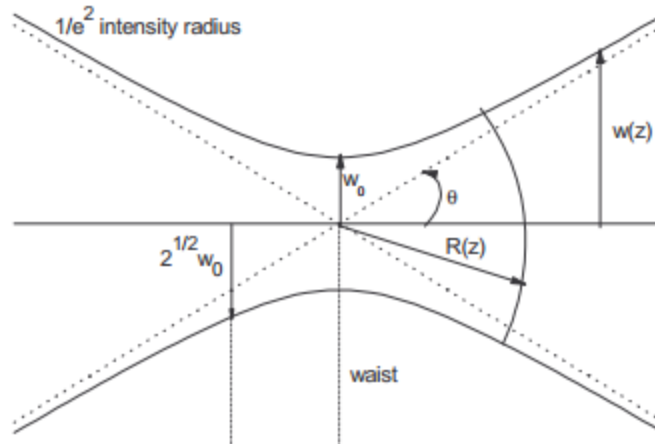
$$b = Im\left(\frac{1}{q_{1+i}}\right)$$ (2.2.12)

Fig 10. Gaussian beam parameters in $1/e^2$ (Rayleigh range) units. The beam divergence angle is $\theta = \frac{\lambda}{\pi w_0}$ Source: [KEDU]

2.3. Knife edge response

Using the previous analysis, the location of the minimum beam waist can be predicted for any point in an optical system. In order to actually find the minimum beam spot, i.e. the "true" focal point of our system, the knife edge response is a useful tool. This is important because the focal point of a lens and the actual beam width are not the same for the focal length, f, and z_R is the Rayleigh range [VLE]:

$$z_M = \frac{f}{1 + \left(\frac{f}{z_R}\right)^2}. \tag{2.3.1}$$

The principle of this technique is to place a straight edge such as is found on a knife or razor into the path of a laser beam. The power of the clipped beam is measured as a function of the edge position moving into the beam. The system is measured from maximum power to zero power.
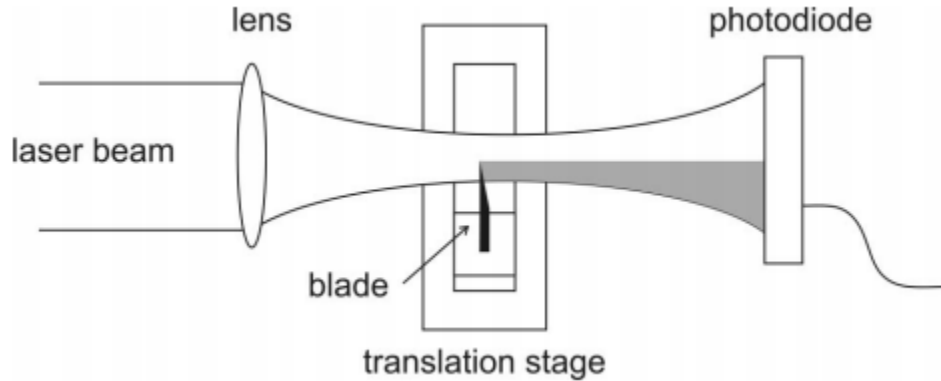
Fig 11. Schematic of knife edge response measurement. Source: [GKET]

The result of this measurement is the integral of the (usually Gaussian) beam from $-\infty$ to the position of the knife, X [KEDU]:

$$P(X) = P_{TOT} - \iint_{-\infty}^{X} I(x,y)dxdy, \qquad (2.3.2)$$

Where

$$P_{TOT} = \iint_{-\infty}^{\infty} I(x,y)dxdy, \qquad (2.3.3)$$

And

$$I(x,y) = I_0 exp\left[\frac{-2x^2}{w_x^2}\right] exp\left[\frac{-2y^2}{w_y^2}\right], \qquad (2.3.4)$$

for a Gaussian beam of width w_x in the x direction and w_y in the y direction.

Therefore, the derivative yields the actual profile of the beam, which we call the linespread function. Depending on where the knife edge measurements are taken will give a different width of the Guassian-like profile. We repeat at different distances along the beam until we find the smallest beam width. According to [WHPP], we need a beamwidth of 30 μm or less incident on the VECSEL structure in order to achieve continuous-wave lasing output.

2.4 Results

From the Gaussian q parameter we calculated the beam waist to be 26.6194 μm at a location of 9.925 cm from the pump laser. A thing to note is that the focal length of the second lens is 10 cm, with an associated waist of 965.1506 μm.
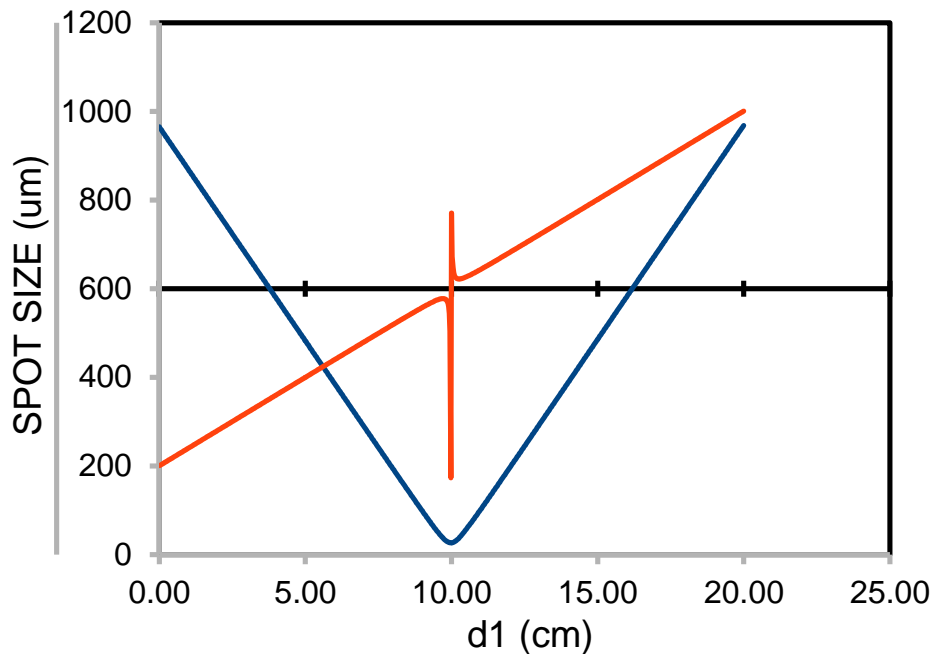

Fig 12. Calculated beam waist (blue) and radius of curvature (red). The computational restraints of the plotting program does not show the divergence to $\pm$ infinity of the radius of curvature

Using knife-edge response, we see that the beam waist is actually 26.885 μm (a relative error of .988 %), and occurs at (approximately) 9.90 cm from the second lens (a relative error of .25%). An interesting thing to note is that the 30 μm radius requirement from [WHPP] is only met at $\pm$ .5 mm of the located minimum spot size.
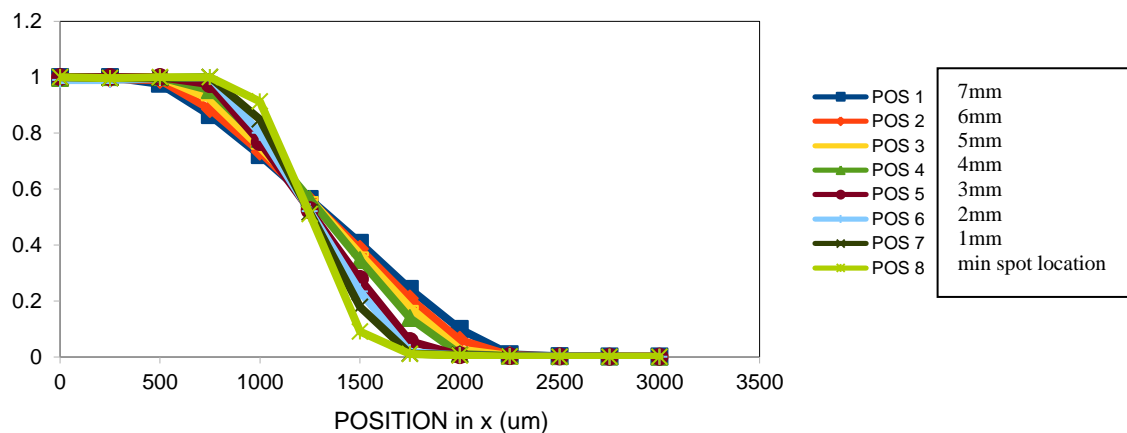
KNIFE EDGE RESPONSE

Fig 13. Power distribution as a function of transverse edge distance
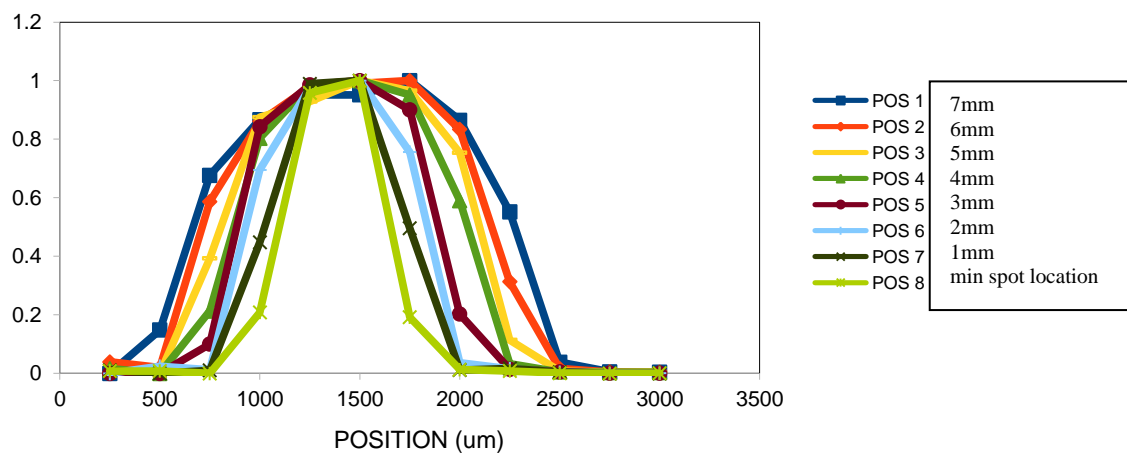
LINE SPREAD FUNCTION

Fig 14. Derivative of knife-edge response, yielding beam width at various distances.

CHAPTER 3

CONTINUOUS WAVE LASER OPERATION OF A VECSEL

3.1. High Power Operation and Diffraction-limited beam quality

A laser beam is considered to be diffraction limited if it has ideal beam quality, i.e., if it has high potential to be focused to small spots [RPDL]. This is equivalent to having an M^2 value close to one. M^2 is called the beam quality factor or beam propagation factor and is given by [RPM2]:

$$M^2 = \frac{\theta \pi w_0}{\lambda}$$
(3.1.1)

A perfectly diffraction-limited beam has $M^2 = 1$, typified by a Gaussian beam. In general, TEM_{nm} modes have M^2 values given by $(2n + 1)$ in the x direction and $(2m + 1)$ in the y direction [RPM2].

The first high power diffraction limited beam was accomplished with a diode-pumped VECSEL structure operating at 808 nm and 2 and 3 W [KVX1]. The experiment used a strain-compensated InGaAs-GaAsP-GaAs multiple quantum well structure as the gain medium. The output centered on 1004 nm with a power of .69 W in a TEM_{11} mode and .52 W in a TEM_{00} mode. The lasing cavity was made from a highly reflective mirror on the chip that provides gain, and an external spherical mirror which controls transverse mode operation of the laser. This essentially divides optical functionality between the laser pump and the actual laser.
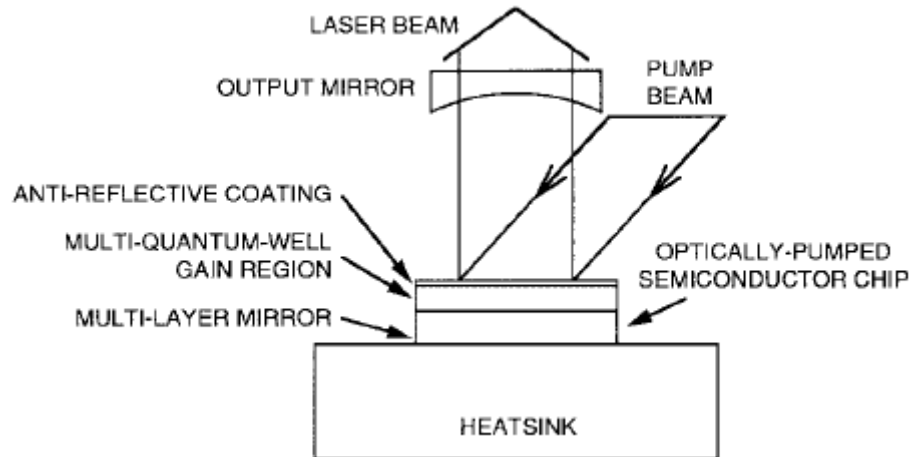
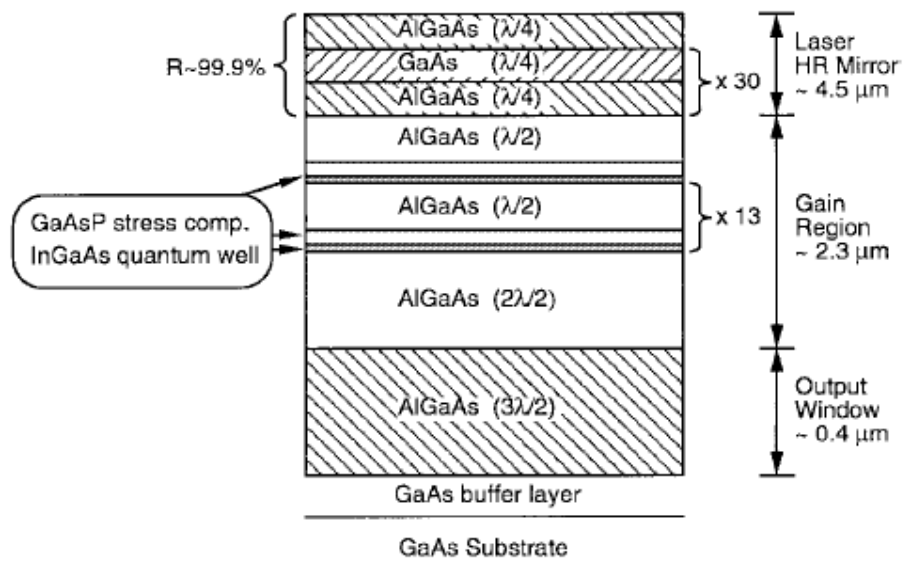Fig 15. Schematic of VECSEL system from reference [KVX1]

Fig 16. Schematic of VECSEL gain substrate structure from reference [KVX1]
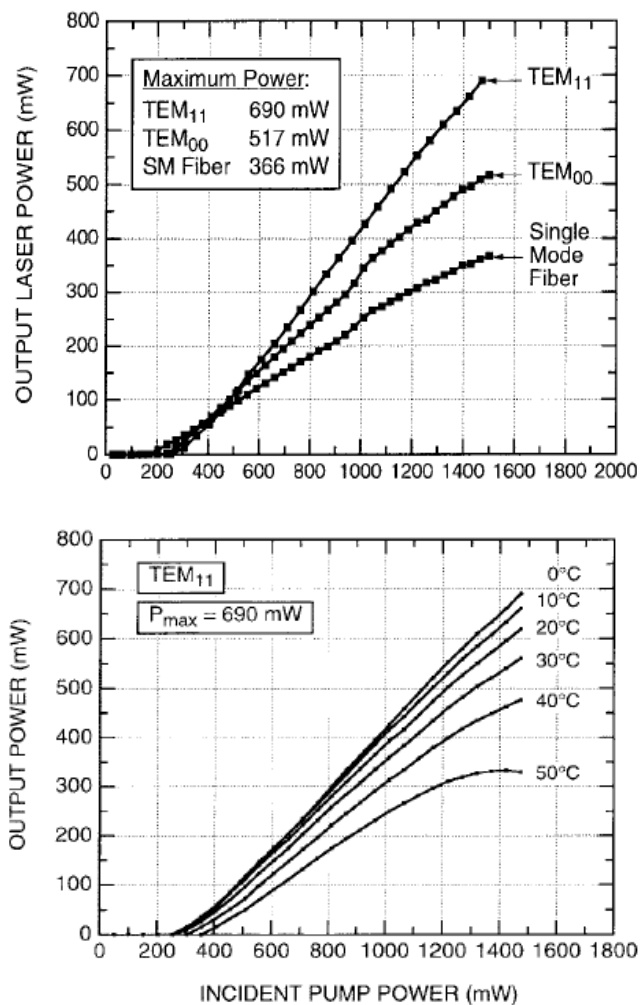
Fig 17. Output power versus incident pump power by lasing mode; and by temperature for different outputs from reference [KVX1]

KW peak powers with perfect M^2 and tunability over 20 nm was accomplished using an organic medium and external resonators in reference [RHOL].

3.2. Intra-cavity frequency doubling (ICFD)

ICFD is a way to achieve visible radiation. As most VECSEL systems lase in the IR, frequency doubling is used to reduce the lasing wavelength to visible ranges. Frequency doubling is a nonlinear interaction of light with matter resulting from that material's nonlinear response with (usually intense) light. It is a consequence of conservation of energy and a type of second harmonic generation [RPFD].
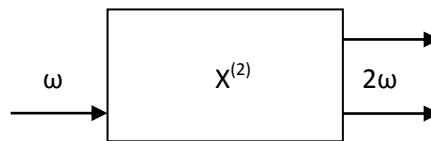

Fig 18. Geometry of second-harmonic generation in a second-order nonlinear medium such that $\omega + \omega = 2\omega$ by energy conservation. Adapted from Reference [BNLO]

Due to the structure of the VECSEL, this can be done inside of the optical cavity. This is useful for two main reasons [RPFD]:

1. Optical intensities are much greater inside of optical cavities than out, allowing greater conversion efficiency.

2. Unconverted power remains in cavity instead of being lost; allowing output comparable to unconverted frequency.

An example of ICFD in a VECSEL structure was reported in [LVXB]. This particular setup is electrically pumped. Due to the external cavity, higher powers are obtained than in a typical VCSEL setup. Also, it forces TEM00 modes by controlling the transverse modes.
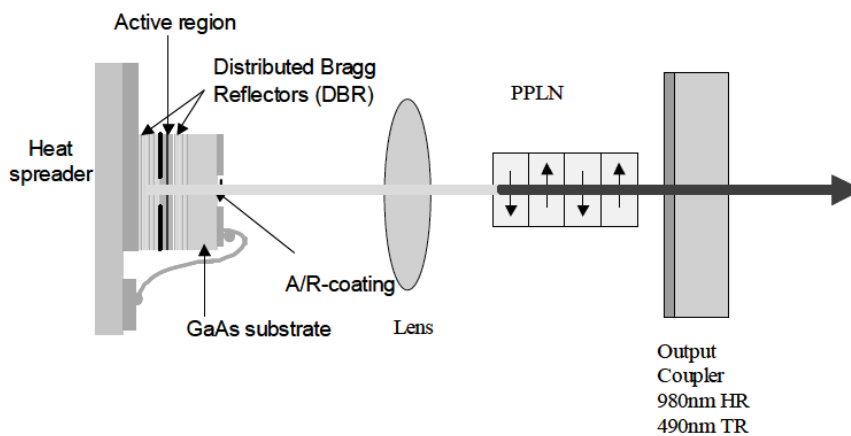
Fig 19. Experimental setup for intracavity frequency doubling taken from reference [LVXB]
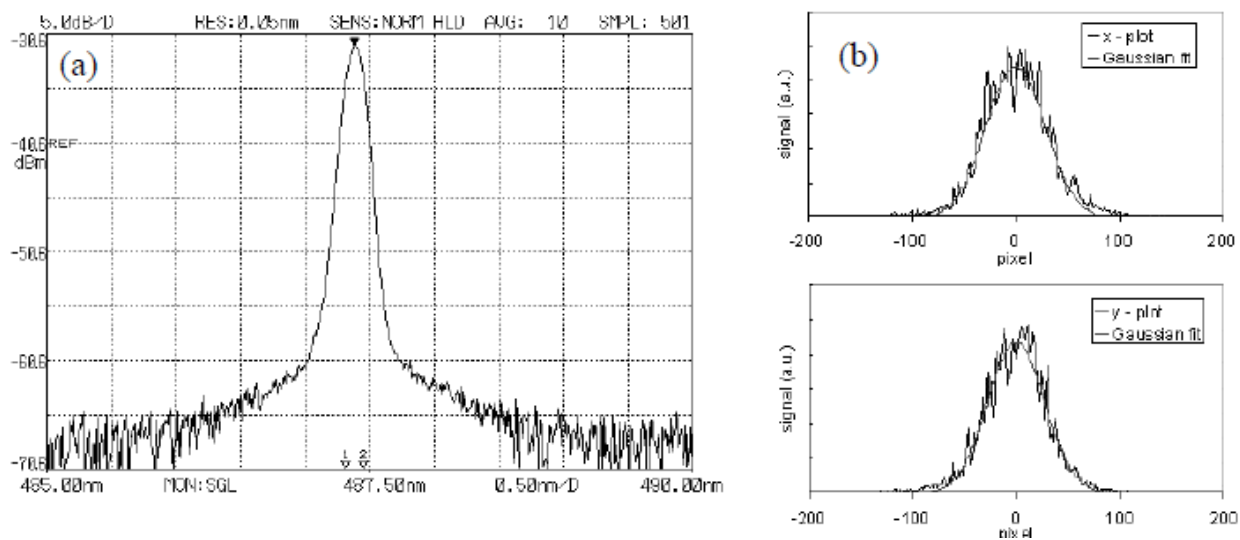

Fig 20. Spectral and Spatial properties of second harmonic output taken from reference [LVXB]

3.3. Spectral Coverage and Tunability

VECSELs of different material systems have operated over the full visible spectrum of

infrared to ultraviolet. The causes of this tunability range from strains on the quantum

well, to ICFD, to adjusting element concentrations in the gain medium [THEC]. Being

that VECSELS are solid state structures, their lasing wavelengths can also be engineered

in processing. In an external cavity, setup wavelengths can also be chosen based on

cavity parameters/output couplers and temperature control. Furthermore, an extended

cavity allows the insertion of spatial and/or spectral filters [RHOL].

We revisit [RHOL] as an example of tunability for a Vertical External Cavity Surface

Organic Laser (VECSOL). This particular system was pumped with 532 nm optical

pulses of 7 ns duration. A conversion efficiency of 43% was obtained. For .5 ns pump

pulses, 2kW output was obtained. This is likely due to the fact that the organic lifetime is

~ 1 ns. The lasing spectrum was controlled by the lasing layer acting like an intracavity

etalon. The lasing layer was used as such due to larger thickness on the edges than in the

center. Tunability was shown over 20 nm maximum by thickness variation in the sample.

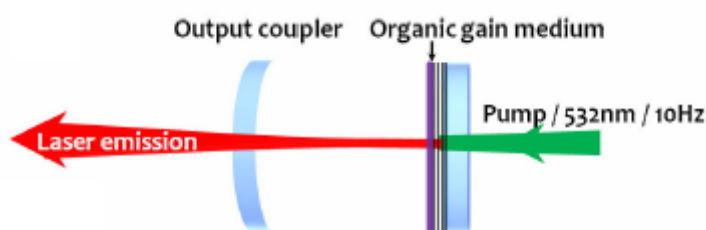It showed power scaling capability with increasing spot size.

Fig 21. Schematic of tunable laser taken from reference [RHOL]
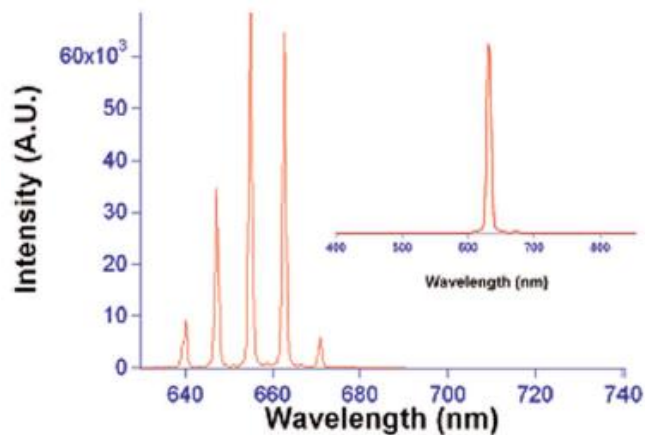
Fig 22. Emission spectrum of 17 μm thick gain medium with 2.35 μm thick layer emission spectrum inset; taken from reference [RHOL]

Fig 23. (a) Spatial evolution of beam output fit to $M^2 = 1$ with TEM_{00} profile inset. (b) TEM_{10} and TEM_{20}; taken from reference [RHOL]

3.4. Particular VECSEL

Fig 24. Quantum well gain structure of Diels lab's 2 VECSELs. Has 6 InGaAs quantum wells tailored for 1040 nm and 1000 nm lasing respectively. Samples are antiresonant

CHAPTER 4

MODE LOCKING AND PULSED OPERATION OF A VECSEL

4.1. Mathematical theory (time)

Mode-locking is a technique used to produce pulses of light with a fixed separation

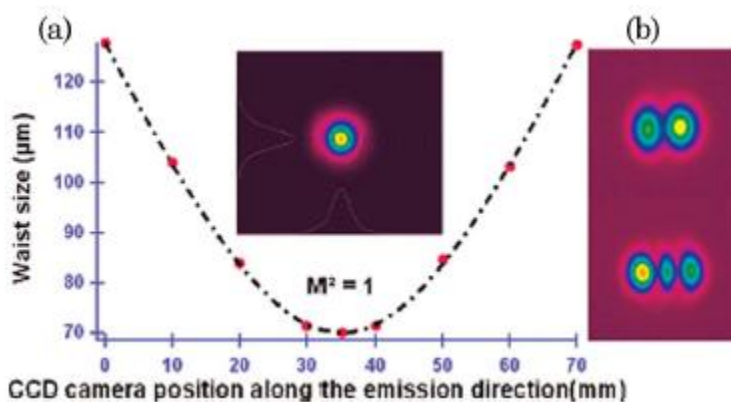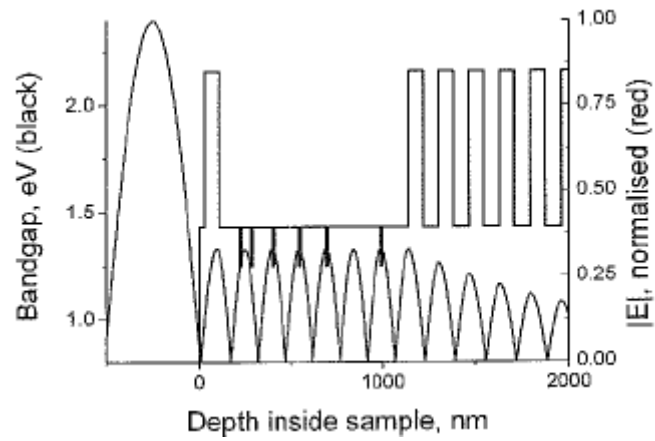between each pulse. Ultrashort pulses are desired for their peak intensities, duration, and

controllable separation. These features allow pulses to be used effectively for

spectroscopy of biological events, extreme nonlinear optics, and timing experiments.

Optical signals travelling in time (a circulating pulse [SL]) can be represented by fields

oscillating with some period, T (the optical cycle period [VLE]). The resonance

condition of the cavity imposes that there be an integer number of light pulses in a cavity

round-trip time, τ. The most important aspects of the time domain picture are the pulse

repetition rate (from the round trip time τ) and the number, N, of modes oscillating

[RPML].

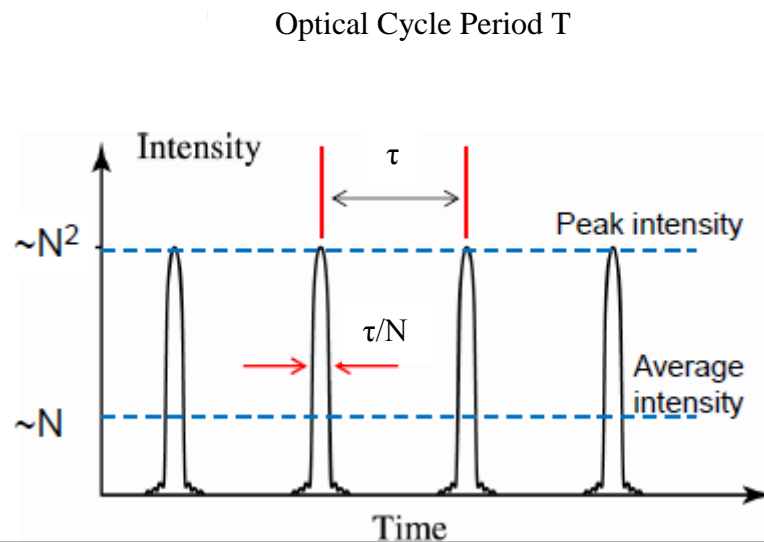Optical Cycle Period T

Fig 25. Temporal depiction of mode-locking for N modes with constant phases
for a real laser. Here, the width of a peak is given by τ/N. We can see that
more modes yields sharper peaks; taken from reference [WAML]

The round trip temporal spacing is the amount of time it takes a photon (or wavefront) to

traverse from one mirror back to the start, i.e. a unit cell for cavity length, d. It is given

by [VLE]:

$$T = \frac{2nd}{c}. \qquad (4.1.2)$$

Mode-locking is when all modes are in phase such that each successive round trip is an

integer multiple of the first round trip with all relative phases at zero. This is in

distinction to mode coupling where amplitude and phase are arbitrary but fixed [MMLS].

The basic premise of active mode locking is that a circulating pulse goes through a

modulator when losses are small, causing pulse "wings" to shorten. The modulation

period exactly matches an integer multiple of the round trip time of the cavity [SL]. Each

multiple of the cavity gives the number of pulses active in the cavity. The losses are

modulated by a cavity control element, usually an acousto-optic modulator (AOM) or

electro-optic modulator (EOM) that is electronically controlled. This essentially reduces

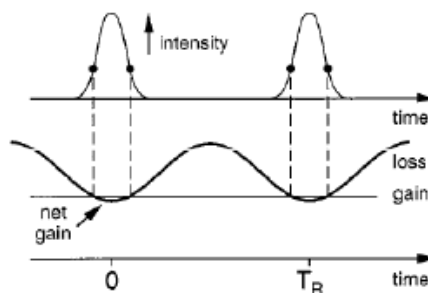broadening inherited from other processes [RPML].

Fig 26. Temporal depiction of mode-locking based on active modulation of cavity losses; taken from reference [MMLS]

4.2. Mathematical theory (frequency)

Optical Signals can also be analyzed in frequency. Both analyses are related to each other through the Fourier transform. The term mode locking comes from the frequency domain. Pulses are formed when frequencies present in a system all have a fixed phase relationship with respect to each other, i.e. are "locked" in phase [RPML]. The pulses are overlapping regions of constructive interference of different waves' amplitudes. Pulsewidths are intimately related to the bandwidth of the medium, Δv, through [VLE]:

$$\Delta \tau_p \approx \frac{1}{2\pi\Delta v} \tag{4.2.1}$$

From this, we can see that gain media with very large gain bandwidth (hence, wavelength tunability) are desired for short pulse production. The modes are spaced at the inverse of the round trip time: $1/\tau$.
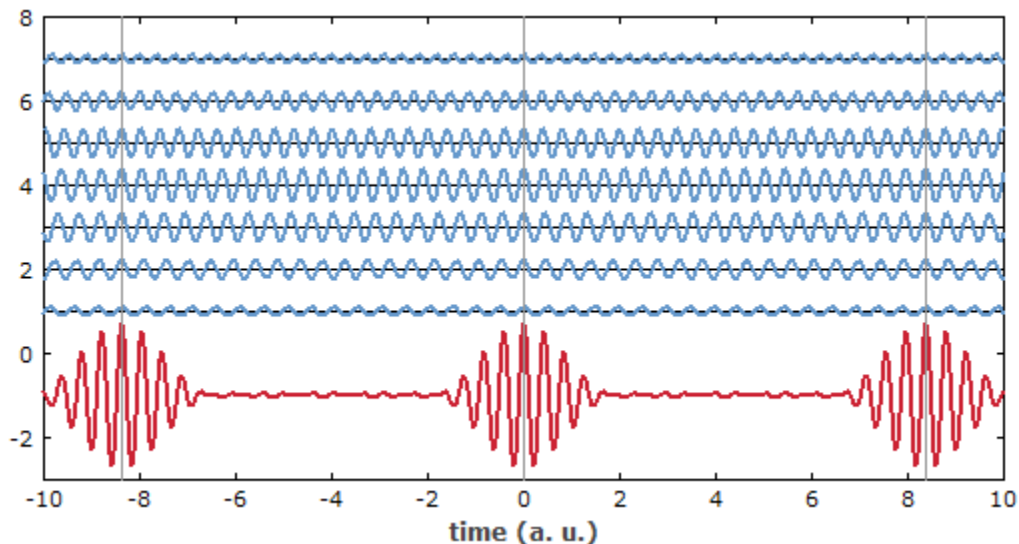

Fig 27. The formation of optical pulses from periodically in phase frequencies, here 7 frequencies are used as an example; taken from reference [RPML]

4.3. SEmiconductor Saturable Absorber Mirror (SESAM) principles

SESAMs are a type of material (such as a quantum well or semiconductor material [KOCW]) used for passive mode locking, touting the production of shorter pulses than active mode locking. They are mirrors with incorporated saturable absorbers [RPML]. These systems embody the principle of passive mode locking: intensity-dependent gain or loss. This simply means that either cavity loss is minimized by high intensities or cavity gain is maximized by high intensities. The SESAM uses the effect of slow saturable absorption to introduce saturable loss to the laser [WTHS].
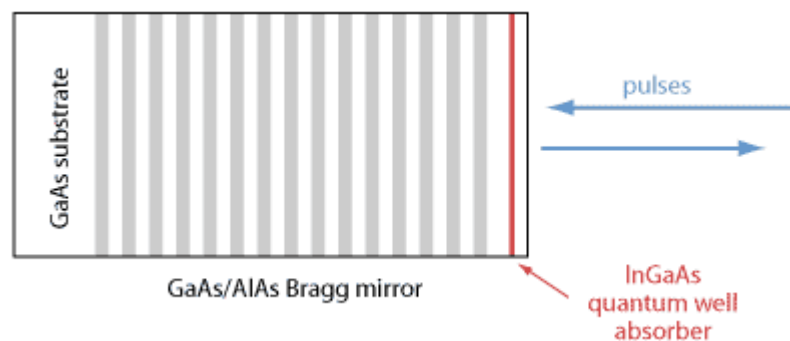
Fig 28. Physical structure of a typical SESAM; taken from reference [RPSM]

The net loss per round trip is reduced for a circulating pulse with high peak power. This occurs because a certain segment of the fluctuating continuous-wave laser signal eventually achieves more gain compared to other modes for each round trip. Eventually, this "spike" becomes amplified into a single pulse, drawing all photons into its modes and its physical space, shrinking the pulse in time and expanding the number of oscillating modes. In total, all cavity losses are lower than the CW case [WTHS].

4.4. Particular SESAM

Fig 29. Physical structure of the identical SESAM used in a previous experiment. As we see SESAMs are similar to VECSEL in design; taken from reference [WTHS]

CHAPTER 5

SUMMARY and OUTLOOK

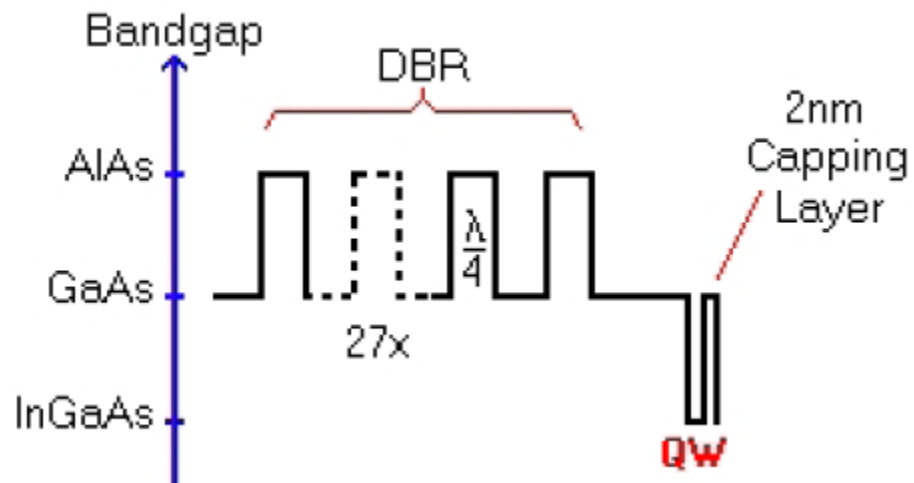In conclusion, we have reviewed laser operation. We then demonstrated how VECSELS show a combination of useful features such as: High power, optimum beam quality, short pulses, a broad wavelength range and tunability, and intracavity frequency doubling. These features, individually or combined, make VECSELs a prime area of research and give them potential to be at the center of laser research and industrial applications.

Future directions are power scaling and integrated structures. VECSEL structures are small and can be combined in a linear manner or fabricated together. This gives them potential for cheap, mass production. Mode locked integrated external-cavity surface emitting lasers (MIXSELS) are a particular type of VECSEL structure with the integration of the absorber and the gain medium in a single semiconductor device, enabling mode locking in a straight cavity [MMIX].

APPENDIX

DERIVATION OF PARAXIAL WAVE EQUATION

Starting from the wave equation for the electric field in a homogenous medium of index n

and speed of light c:

$$\nabla^2 E = \frac{n^2}{c^2}\frac{\partial^2 E}{\partial t^2} \tag{A.1}$$

We define the electric field as the following: An exponential term that yields a plane-like

propagation, U is the departure from a pure plane wave, k is the wave vector of light, ω is

its angular frequency, and φ is its phase:

$$E(x,y,z,t) = U(x,y,z)e^{i(kz-\omega t+\varphi)} \tag{A.2}$$

Substituting this expression into (A.1), we arrive at:

$$e^{i(kz-\omega t+\varphi)}\left[\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} + 2ik\frac{\partial U}{\partial z} + \frac{n^2\omega^2}{c^2}U - k^2 U\right] = 0 \tag{A.3}$$

And since $k = \frac{n\omega}{c}$, we substitute this into (A.3) and arrive at an exact wave equation:

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} + 2ik\frac{\partial U}{\partial z} = 0 \tag{A.4}$$

Next, we take the slowly varying (in z) approximation such that,

$$\left|\frac{\partial^2 U}{\partial z^2}\right| \ll 2ik\left|\frac{\partial U}{\partial z}\right| \tag{A.5}$$

Therefore, we arrive at the paraxial wave equation:

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + 2ik\frac{\partial U}{\partial z} = 0. \tag{A.6}$$

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