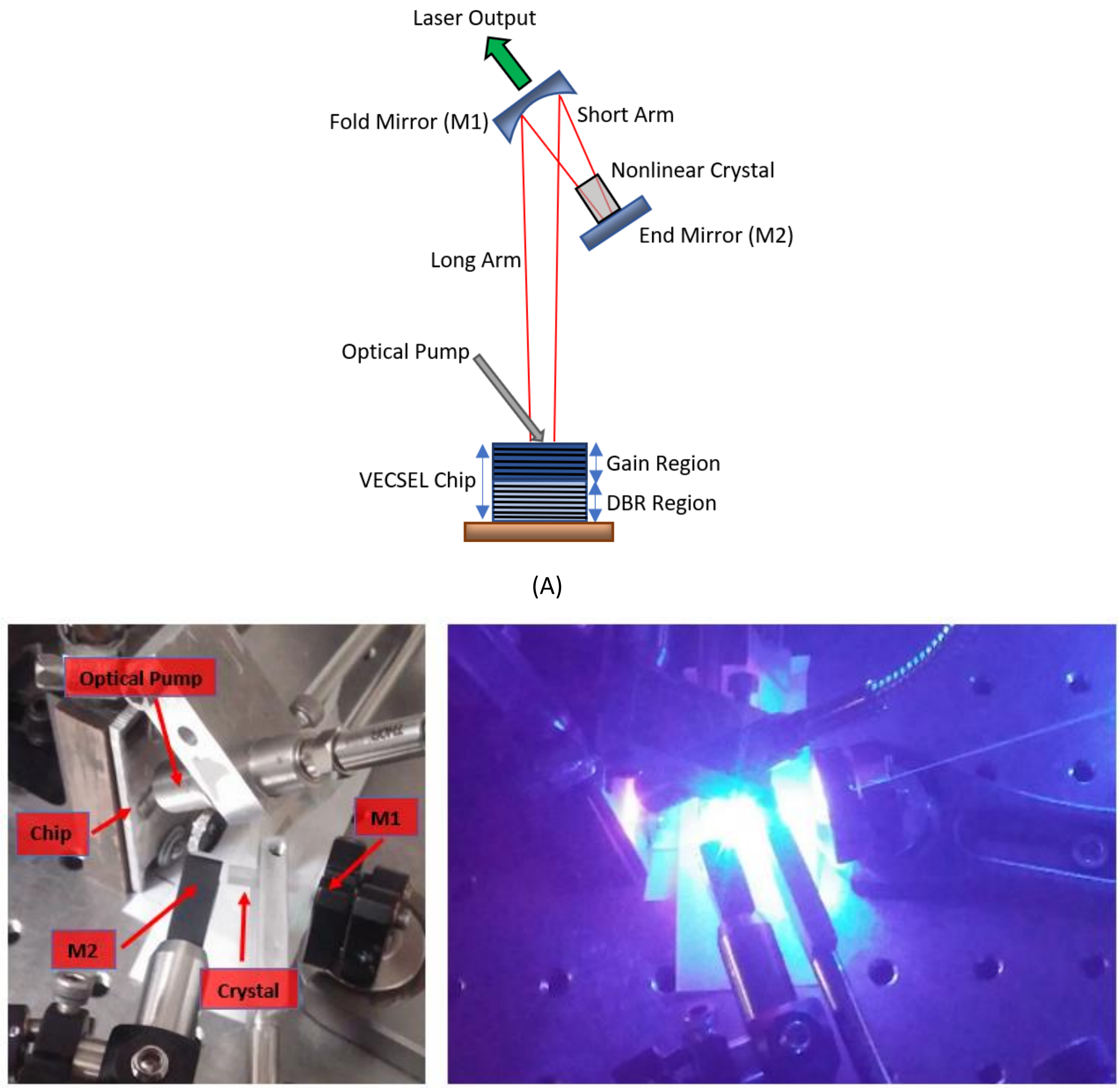
# Vertical External Cavity Surface Emitting Lasers (VECSELs): A flexible laser platform with a high degree of customization

## 1. Introduction

Over the past few decades, lasers have become a robust tool used in areas as diverse as defense, medical, telecommunications, etc., for a wide array of tasks, such as detection and range finding, material processing, and semiconductor fabrication. Depending on the application, a specific type of laser will be selected that is best able to meet the requirements of the end user. Some of these parameters might include high output power, wavelength selection, tunability, pulsed or continuous wave operation, power efficiency, and package size. Within the laser community is an interesting laser variant known as a VECSEL, or Vertical External Cavity Surface Emitting Laser. While not nearly as popular or well known as more common lasers like the Excimer, Nd:YAG, or Ti:Sapphire, VECSELs offer a unique ability to the end user to select a range of parameters that can be custom built and suited to a specific application. The VECSEL has been demonstrated to be capable of simultaneously providing widely tunable, two color laser beams by using a combination of semiconductor chips, polarizers, beam splitters, and nonlinear optical crystals[1].

Becoming proficient at VECSEL design, simulation, and construction requires a robust and expansive knowledge of optical science and engineering. An integral part of the VECSEL is the semiconductor chip which contains both the gain medium and a Distributed Bragg Reflector (DBR), which acts as one of the end mirrors in the laser cavity. Proper chip design requires knowledge of quantum mechanics, laser physics, and beam propagation. Constructing an efficient laser cavity also requires deep knowledge of laser physics, as well as knowledge of Gaussian beam propagation, geometrical optics, and optical engineering. Operation of the VECSEL might require the insertion of nonlinear optical crystals for frequency conversion, which then requires knowledge of Maxwell's equations which give rise to the polarization, a primary component of the frequency conversion process. Even testing the performance of the laser requires great understanding of yet another field, that of photonics, for proper detection and analysis of the laser beam. It is practically impossible to entirely neglect any field in optics if one expects to work successfully on VECSELs.

A VECSEL in a V-cavity configuration, observed in Figure 1, contains a semiconductor chip, two mirrors, a nonlinear optical crystal, and an optical pump laser. The semiconductor chip contains both the gain media and a distributed Bragg reflector (DBR), which acts as a third mirror. The fold mirror (M1) is a curved mirror and the end mirror (M2) is a flat mirror. The distance between the chip and fold mirror is referred to as the “long arm,” whereas the distance between the fold mirror and the end mirror is referred to as the “short arm.” A nonlinear crystal is usually placed near M2 in the short arm for second harmonic generation. The significance and flexibility of this design will be explored in the coming sections.




(B) (C)

Figure 1. VECSEL in a “V-cavity” configuration (A). The image observed in (B) is an example of a V-cavity designed for a fundamental wavelength of ~940 nm and second harmonic generation of ~470 nm. The image observed in (C) demonstrates high-power operation of the second harmonic with this cavity.

## 2. VECSEL Chip Structure

The heart of any VECSEL is the semiconductor chip, which contains both the laser gain media and a distributed Bragg reflector, which acts as an end mirror (Figure 2). This type of laser is sometimes referred to as a multi-quantum well laser (MQW) because the gain region is a combination of a series of quantum wells sandwiched between barriers. The combination of the gain region with the DBR will create a microcavity that will support its own standing wave. The quantum wells are ideally positioned at the location of the antinodes of this standing wave, leading to a condition referred to as resonant periodic gain. For a MQW laser, the gain can be defined as[2]

$$g(E,N) \propto \frac{\Gamma D(E)|M|^2[f_c(E,N) - f_v(E,N)]}{E} \quad (1)$$

where $\Gamma$ is the optical confinement factor, $D$ is the density of states for a quantum well, $|M|^2$ is the matrix element for the energy level transition, and $f_c/f_v$ are the Fermi energies for the conduction and valence bands, respectively. The factor $N$ represents the carrier density for electrons and holes, which is assumed to be equal since our chip is undoped.

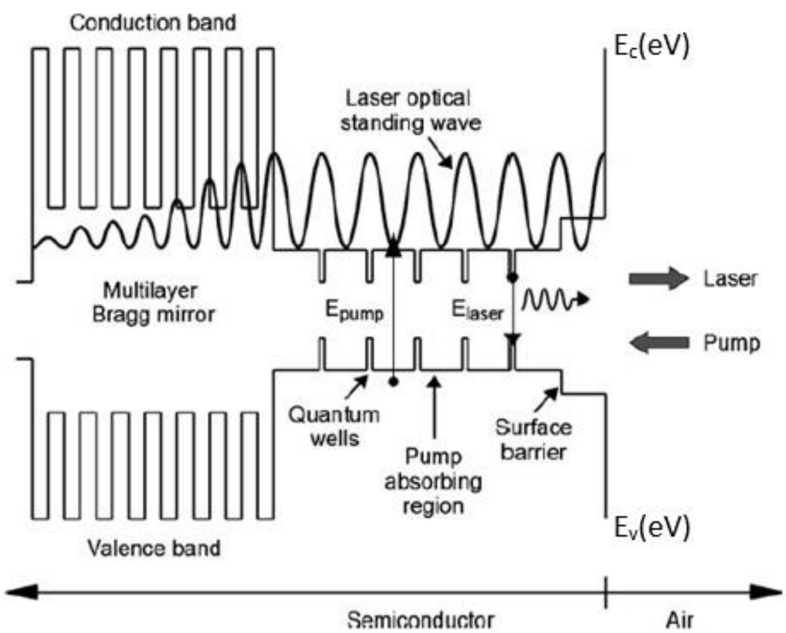



Figure 2. VECSEL semiconductor chip structure. Source: Semiconductor Disk Lasers by Oleg G. Okhotnikov.

The gain is largely driven by the confinement factor, which is the ratio of the light intensity of the lasing mode within the active region with respect to the total intensity of the electric field[2]. When you consider a chip designed for a fundamental lasing wavelength of 1550 nm, the ideal quantum well width is approximately 7 nm. This will result in a low confinement factor which places a fundamental limitation on the available gain of the chip. This is partially compensated by having several iterations of quantum wells located at the standing wave antinodes, but even this has a limit. If you consider a simple semiconductor chip that has a single layer of InGaAsP, with an absorption coefficient of approximately ~1000 $cm^{-1}$ at a pump wavelength of 1200 nm, the Beer-Lambert law tells us that we can expect the electromagnetic field strength of the pump to be reduced to 1/e of its initial value at a penetration depth of ~10 μm. When you consider the refractive index of the material for the exact location of the antinodes, it becomes apparent that you can only expect to place a finite number of quantum wells within the structure before most of your pump photons have been absorbed. This can lead to a relatively weak gain of the VECSEL in comparison to Nd:YAG or Ti:Sapphire and is a major design consideration.

The gain structure, designed for absorption of the pump photon energy, will essentially be transparent to the generated fundamental photons because the fundamental photon energy will be lower than the bandgap energy of the barriers. The DBR is designed for maximum reflection at the fundamental wavelength. This section consists of two alternating layers with different refractive indices, each a quarter wavelength thick with an optical path difference between two layers being equal to a half wavelength. This design leads to constructive interference between all the reflecting wave components, since each component will have a relative phase difference of 0° or 360°, and a maximum reflectivity will be achieved. When designed correctly, the DBR can achieve reflectivity >99.9%. The so called "stopband" of the DBR, or the range of wavelengths over which this maximum reflectivity occurs, increases with a larger difference between the refractive indices of the layers.

### 3. Pumping Mechanism

When using an optical pump scheme, photons emitted by the pump will penetrate the chip. The bandgap of the barriers will determine the minimum optical pump photon energy needed for absorption and is driven by

$$E\ (eV) = \frac{1.24}{\lambda(\mu m)}\ . \tag{2}$$

The wavelength is inversely proportional to the bandgap energy, which means that a larger barrier bandgap will require a shorter pump wavelength. For example, if you are using an optical pump emitting at 1200 nm, the corresponding photon energy is 1.02 eV. This places a requirement on the design of the barrier to have a bandgap of less than 1.02 eV in order to absorb the pump photons. If the energy of the pump photon is equal to, or exceeds, the bandgap energy of the barriers, an electron will be excited from the valence band to the conduction band as the pump photon energy is absorbed. This electron will then diffuse into the quantum well and occupy one of the available quantized energy levels. When an electron drops down from an energy level in the conduction band quantum well into the corresponding valence band energy level, a photon will be emitted that has energy equivalent to the energy lost during the transition.

The size of the optical pump spot on the chip is important when considering the minimum pump power needed to reach the lasing threshold. For a fixed pump spot size on the chip, this pump power results in a minimum power density required to achieve population inversion, a condition where absorption of pump photons leads to more charge carriers in the conduction band than the valence band. Until this condition is met, total cavity loss exceeds gain and lasing is not possible. However, the power density provides flexibility in design. A weaker optical pump power can be compensated with a smaller pump spot sized on the chip to reach threshold.

## 4. Cavity Design and Optical Engineering

To achieve a stable V-cavity configuration, it is necessary for the Gaussian beam to have a beam waist at both the location of the chip and M2, since they are optically flat surfaces. The V-cavity could be understood through the eyes of geometric optics as essentially a linear cavity, if one unfolds M1 about the optical axis and treats the unfolded mirror as a thin lens with equivalent optical power, with the object plane being the location of the chip and the image plane being the location of the end mirror (Figure 3).

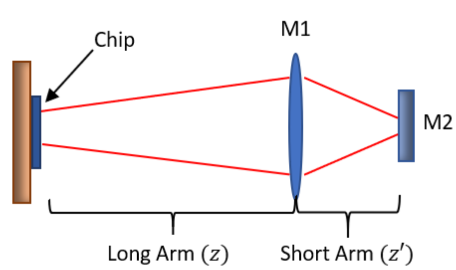



Figure 3. Geometrical representation of unfolded V-cavity. Fold mirror M1 is now represented by a thin lens with similar optical power.

The thin lens will focus the optical pump spot on the chip to a corresponding image at M2 based on the magnification. The location and size of the pump spot at M2 can be defined by the simple geometric optics equations

$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f_E} \quad , \quad m = \frac{z'}{z} \quad , \quad h' = mh \tag{3}$$

where $z'$ is the short arm length, $z$ is the long arm length, $h'$ is the radius of the beam at M2, $h$ is the radius of the beam at the chip, $f_E$ is the effective focal length of the lens, and $m$ is the magnification. If we consider a cavity that has a circularly symmetric pump spot on the chip with a diameter of 200 µm, a 3.8 cm radius of curvature mirror (M1) with a corresponding focal length of 1.9 cm, and a long arm length of 4.5 cm, we can calculate the short arm length to be 3.3 cm with a beam diameter of ~145 µm at M2. This approach provides a general idea of the cavity geometry as it pertains to object/image distances and general magnification, but it assumes previous knowledge of the supported Gaussian beam waist located at the chip. The solution to this problem will be explored in Section 5.

One of the problems created by the V-cavity geometry is astigmatism of the Gaussian beam caused by the fold angle of the fold mirror. Astigmatism is understood as the creation of an elliptical beam spot formed by the tangential and sagittal ray fans seeing different system powers, thus focusing to different positions along the optical axis. We introduce this error into the cavity by using a circularly symmetric fold mirror rotated at an angle along a vertical axis to form the V-cavity. Optical rays along the tangential ray fan see no difference in optical power with this rotation. However, sagittal rays will impact the mirror at different locations, experiencing a different optical power than the tangential rays. This leads to an elliptical Gaussian beam profile within the cavity.

## 5. Beam Propagation and Nonlinear Optics

While geometric optics allows a general description of the object-image relationship within the cavity, it does not provide a rigorous definition of the Gaussian beam properties inherent to a laser beam. The V-cavity is a laser beam resonator, which means that after the electromagnetic field within the cavity completes one round trip, the field exactly replicates itself for a fixed position in space. The Gaussian beam within the cavity needs to be a solution of the paraxial wave equation and should take the form of[3]

$$E(r) = A\frac{w_0}{w(z)} e^{i\left[kz - \tan^{-1}\left(\frac{z}{z_0}\right)\right]} e^{-i\omega t} e^{ik(x^2+y^2)/2R(z)} e^{-(x^2+y^2)/w^2(z)}. \tag{4}$$

The most important parameters when characterizing a Gaussian beam include the beam waist $w_0$, the Rayleigh range $z_0$, the beam size $w(z)$, and the wavefront radius of curvature $R(z)$. The beam waist is a location where the wavefront radius of curvature is infinite, resulting in a plane wave. Within the V-cavity geometry of Figure 1, there will be two locations where there needs to exist a planar wavefront:

at the chip and at the end mirror. When properly designed, the wavefront radius of curvature at the fold mirror will exactly match the physical curvature of this mirror. This is the basic criteria for obtaining a stable resonator.

A limitation of the approach detailed in Section 4 involving the use of geometric optics to design a cavity is that it assumes previous knowledge of the actual supported beam waist size at the chip. It is incorrect to assume that a stable resonator will be formed with an arbitrary selection of pump spot size at the chip. When modeled based on Gaussian beam physics, the cavity described in Section 4 results in a highly astigmatic beam, with a major axis diameter of 136 µm at the chip and 96 µm at the end mirror. Not only has the actual size of the beam spots changed, but the magnification has changed as well: 0.705 for the Gaussian approach vs. 0.725 for the geometrical approach. To design this cavity using only geometrical optics, you would have needed to know beforehand that the supported spot size at the chip had a major axis diameter of 136 µm.

The importance of correctly modeling the Gaussian beam propagation within the cavity becomes more apparent with the insertion of a nonlinear optical crystal into the short arm. The nonlinear optical crystal exhibits a second order optical nonlinearity, $\chi^{(2)}$, which leads to the generation of a nonlinear polarization responsible for phenomena such as second harmonic generation and sum frequency generation. In second harmonic generation the fundamental wavelength is converted to its second harmonic which is at half the wavelength or twice the frequency. Certain materials exhibit strong $\chi^{(2)}$ nonlinearities at specific fundamental wavelengths, such as lithium triborate (LBO) or beta barium borate (BBO) crystals.

One of the key parameters that drives the conversion efficiency of a nonlinear crystal is the location and size of the Gaussian beam waist within the crystal. The second harmonic power generated by a nonlinear optical crystal can be expressed as[4]

$$P_{2\omega_1} = K\left[\frac{128\pi^2\omega_1^3 d_{eff}^2}{c^4 n_1 n_2}\right](2.84 k w_0^2) P_{\omega_1}^2 \quad (5)$$

where $\omega_1$ is the fundamental frequency, $d_{eff}$ is the effective nonlinear optical coefficient, $c$ is the speed of light, $n_1$ and $n_2$ are the refractive indices of the crystal at the fundamental and second harmonic wavelength, $k$ is the fundamental wave number, $w_0$ is the Gaussian beam waist, and $P_{\omega_1}$ is the power of the fundamental beam. One of the major considerations for greater second harmonic power generation is achieving the correct beam waist size, $w_0$, within the crystal since there is a quadratic relationship between the beam waist and the second harmonic power generated. The ideal beam waist is defined as[5]

$$w_0 = \sqrt{\frac{\lambda L}{(2\pi)(2.84)}} \quad (6)$$

with $\lambda$ being the fundamental wavelength and $L$ being the length of the crystal. This waist should also be located at the center of the crystal[5]. This beam waist size is usually smaller than the pump spot size on the chip when you consider practical cavity geometry and the pumping mechanism. When the nonlinear crystal is inserted into the cavity, it can take advantage of the high circulating power of the fundamental beam, $P_{\omega_1}$, which will also lead to a greater conversion efficiency. Therefore, the ideal location for the crystal would be in a position in the cavity that can simultaneously achieve a smaller beam waist than that on the chip and have that waist be located at the center of the crystal. In a V-cavity configuration, the only other location that has a usable beam waist is at the end mirror.

If the nonlinear crystal is placed as close to the end mirror as possible, it would still appear as though the beam waist is positioned at the end of the crystal. This might lead to concern that that the crystal is not maximizing its conversion efficiency. However, when you look at the resonator cavity as an unfolded optical system about the end mirror, it becomes apparent that the laser beam is passing through the crystal twice, with the location of the beam waist right in the middle of this double pass (Figure 4). Therefore, an arbitrary crystal, properly positioned against the end mirror, with a physical length of 10 mm will perform like a crystal with a length of 20 mm, with the Gaussian beam waist located at its center.

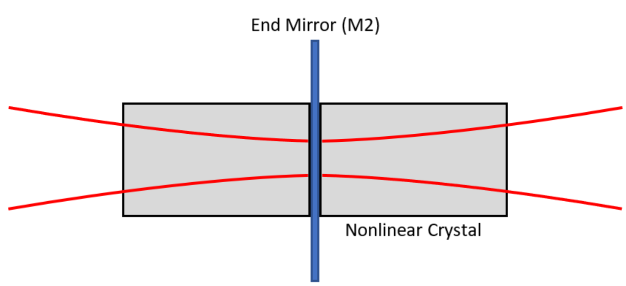



Figure 4. V-cavity unfolded about the end mirror (M2) to demonstrate the double pass through the nonlinear crystal, with the Gaussian beam waist located at the "center" of the crystal.

## 6. Laser Characterization

Characterization of a VECSEL usually involves measuring the output power, the optical spectrum of the output beam, the photoluminescence of the semiconductor chip, and the output Gaussian beam profile. In a V-cavity configuration, the fundamental and/or second harmonic beam can be characterized by selecting an appropriately coated fold mirror. This is usually 1-3% transmissive at the fundamental wavelength, or anti-reflective coated at the second harmonic wavelength. While we want to extract 100% of the second harmonic from the cavity, we only require a small fraction of the circulating fundamental to be extracted for characterization.

The optical spectrum is characterized by coupling a portion of the ejected laser beam into a fiber optic cable connected to an optical spectrum analyzer (OSA) to observe the lasing wavelength and, ideally, single mode operation. The laser beam can be focused into the fiber optic by use of a focusing lens selected and positioned so that the numerical aperture of the lens roughly matches the numerical aperture of the fiber optic connector head. Depending on the output power of the laser beam and the sensitivity of the OSA, it is sometimes possible to simply place a bare fiber in the path of the laser beam and detect a signal.

Another useful measurement is that of the photoluminescence (PL) of the chip. With the laser cavity blocked with a physical obstruction, the core of a bare fiber optic can be brought close (<1 mm) to the chip surface in front of the location of the optical pump spot. With the pump is turned on to a power level above the lasing threshold of the cavity, photons from the pump will be absorbed by the chip structure. Since the barriers in the chip are designed to absorb at the pump wavelength, electron-hole pairs will be created, with the excited electrons in the conduction band diffusing into the quantum wells. Since there is no stimulated emission in this process with the laser cavity blocked, the electron will follow the relaxation time of the semiconductor and emit a photon at a wavelength corresponding to the energy given up when the electron decays to the valence band. The photons emitted by this process are then coupled into the fiber optic for detection by the OSA. The spectral pattern that is observed is referred to as the "PL" of the chip and is an indicator of the relative strength of different reflected wavelength components from the chip.

Finally, the Gaussian beam profile can be measured by insertion of a portion of the outcoupled laser beam into a beam profiler device. This measurement is comparing the profile of the generated laser beam against a profile of a diffraction-limited Gaussian beam defined by[6]

$$\theta = M^2 \frac{\lambda}{\pi w_0} \ . \tag{7}$$

A diffraction-limited Gaussian beam will have an $M^2$ equal to 1 and a good VECSEL design should aim to be as close to this limit as possible.

## 7. Conclusion

The VECSEL is a highly flexible laser platform that allows significant customization. The gain chip can be designed to achieve specific fundamental lasing wavelengths with variable gain. The external cavity allows for customization of the propagating Gaussian beam profile, enabling the user to design for specific beam sizes throughout the cavity based upon cavity geometry and mirror specifications. The accessible external cavity also allows for insertion of additional optical components. We explored the insertion of a nonlinear optical crystal for second harmonic generation, but other components can be inserted depending on the end use of the laser. The high degree of customizability of the VECSEL requires that the laser scientist have a broad and robust understanding of optical physics and engineering principles in order to carry out successful laser research projects and opening doors to new possibilities of VECSEL applications.

The inclusion of a semiconductor saturable absorber mirror in an appropriately designed VECSEL cavity can induce passive mode locked operation. Passive mode locking is different from continuous wave operation in that the laser cavity emits a series of pulses with their spacing “locked” by the repetition rate defined by the cavity round-trip time. Research is being performed that includes adding nonlinear optical crystals to this cavity, resulting in ultrafast second harmonic generation in the visible spectrum, with pulse widths $<1$ ps and peak pulse powers in the hundreds of watts. These results have opened the door to new research involving optimized VECSEL cavity geometries for ultrafast lasing operation at targeted wavelengths in the visible spectrum.

# References


1. M. Lukowski, C. Hessenius, and M. Fallahi, "Widely tunable high-power two-color VECSELs for new wavelength generation," *IEEE J. Sel. Top. Quantum Electron*, vol. 21, no. 1, Jan./Feb. 2015.
2. Bass, Michael. *Handbook of Optics*. Vol. 1, Mc-Graw Hill, 1995.
3. Milonni, Peter W., and J. H. Eberly. *Laser Physics*. A John Wiley & Sons, Inc., Publication, 2010.
4. Boyd, Robert W. *Nonlinear Optics*. Elsevier, Inc., 2008.
5. Boyd, G.D. and D.A. Kleinman, "Parametric Interaction of Focused Gaussian Light Beams," *Journal of Applied Physics*, vol. 39, Nov. 2003.
6. Paschotta, Rüdiger. "$M^2$ Factor." *RP Photonics Encyclopedia*, RP Photonics, 22 October 2019, https://www.rp-photonics.com/m2_factor.html.