Vixar Application Note

Using VCSELs in Atomic Sensors

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1 Atomic Sensors

Atomic clocks and magnetometers based on the optical assessment of Alkali metals such as Rubidium and Cesium offer unprecedented levels of accuracy, precision, and stability. The development of new Vertical Cavity Semiconductor Lasers (VCSELs) with suitable performance has enabled dramatic improvements in system size, weight, and power. The performance advantages of atomic sensors are now within the reach of a wide range of new low cost, portable, and battery-operated applications. While the absolute performance of these new VCSEL-based solutions may not rival their more exotic and sophisticated laboratory-grade counterparts, they have nevertheless enabled a number of new applications in areas such as GPS navigation, undersea mining, networking, medical imaging, military, and civilian communications.

The excitation of the ground state atomic transition levels in alkali metal atoms can be exploited via the mechanism of Coherent Population Trapping (CPT) in the case of atomic clocks and magnetometers. Rubidium (Rb) and Cesium (Cs) are two of the most used elements and have atomic energy transitions in the NIR wavelengths accessible with GaAs-based VCSELs. The absorption lines of ^{87}Rb D1 at 795nm and ^{133}Cs D1 at 895nm are of the most interest for these applications.

Owing to the inherent stability of these transitions, these sensors can themselves be made extremely stable or precise. In its simplest form, an atomic sensor consists of a heated vial containing a mixture of the alkali and buffer gases, a VCSEL as an illumination source, a photodetector for monitoring the optical transmission through the gas mixture, and electronics for system control and signal processing.

There are multiple performance criteria that must be satisfied by the VCSEL to achieve acceptable system performance in these applications. Single mode, narrow linewidth operation and tunability are critical factors. In addition, VCSELs must also be designed with a high degree of polarization stability. Finally, there are other advantages that VCSELs present to the system designer, including low-divergence circular radiation characteristics, low-complexity packaging capability, and wafer-level wavelength binning.

This application note briefly describes the main applications for VCSEL-based atomic sensors including atomic clocks for high-precision timing. VCSEL design features are also reviewed to best meet the performance requirements for these applications.

2 Atomic Clocks

Low power chip-scale atomic clocks have come to be of great interest in the past decade. Synchronization of secure communication networks and navigation in GPS-denied environments are topics of particular importance. A portable atomic clock can be used to hold and bridge the gap until restoration of a lost GPS signal where there is a need for the precise timing synchronization of low power sensor networks. In addition, improved low cost timing systems are required for cellular, telecommunications, and financial applications in both networking equipment and secure communication lines. With the recent advances towards industrialization and volume production, atomic clocks are poised to replace commonly utilized oven-stabilized crystal oscillators for many different high-precision timing applications.

CPT-based atomic clocks utilize the coherent excitation of two resonant states of the Alkali atoms spaced at a specific frequency. For these alkali metals, the relevant energy level of the valence electron's ground state is split into 2 levels due to the hyperfine interaction between nuclear and electron spins. This wavelength spacing, 6.8 GHz and 9.2 GHz for the ^{87}Rb D1 and ^{133}Cs D1 lines respectively, is an inherent property of the atoms regardless of gas temperature and pressure. If these two finely spaced transitions are simultaneously excited with circularly polarized light, the gas undergoes coherent population trapping (CPT) and switches from being a highly absorbing medium to being more transparent. This transition can be observed as an increase in detected VCSEL optical power transmitted through the gas cell.

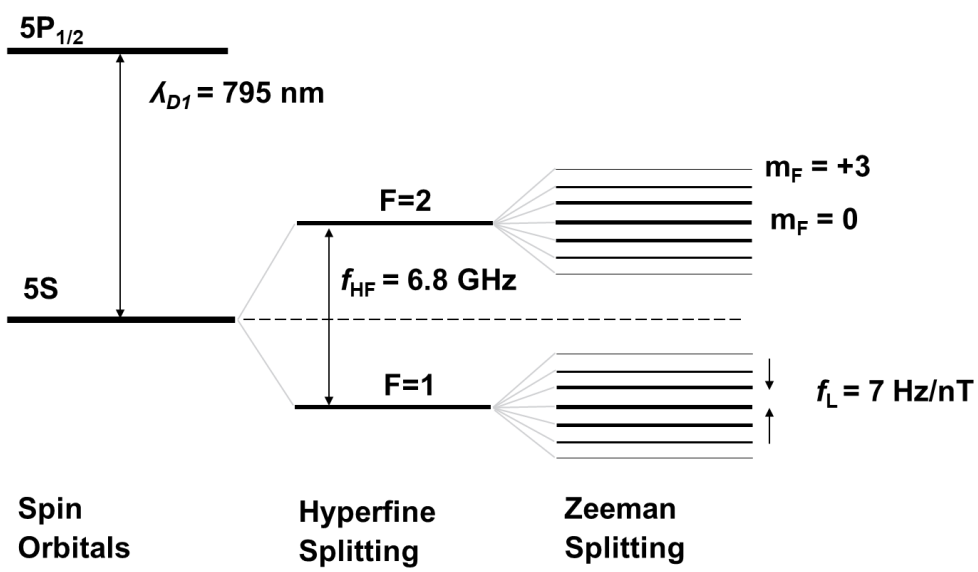

Figure 01: Spectral lines in an Rb atom including hyperfine splitting from electron-nuclear interactions and Zeeman splitting from external magnetic field interactions.

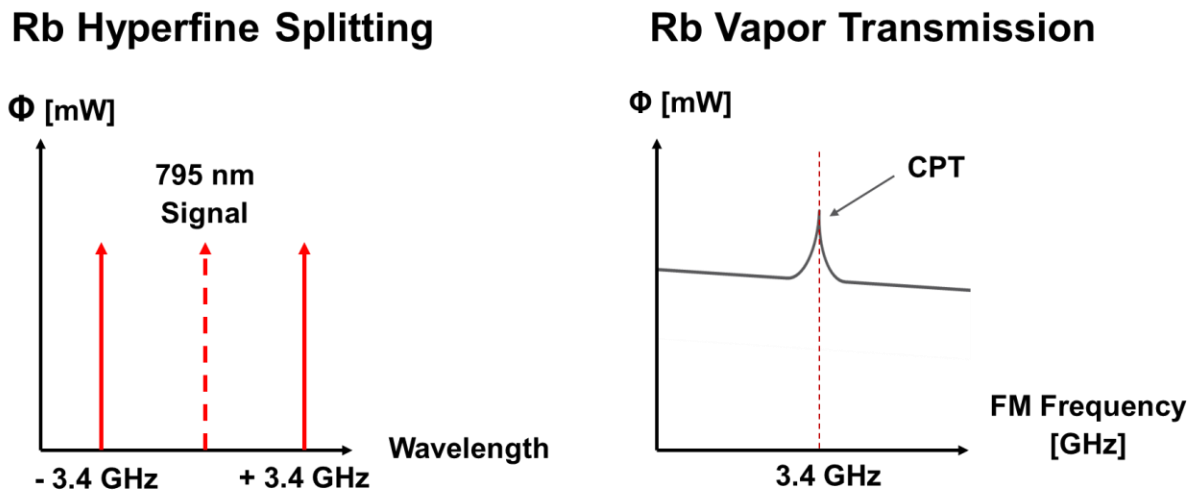

Figure 02: Coherent population trapping (CPT) occurs when both hyperfine spectral lines are simultaneously excited in Rb atoms (left) and power transmission through the gas increases (right).

In an atomic clock, a linearly polarized VCSEL is driven with a modulated current signal to create multiple laser frequency sidebands. The modulated optical signal passes through a quarter wave plate (QWP) to achieve circular polarization required to enforce selection rules for CPT. The VCSEL driving conditions are adjusted until the detected power at the photodiode (PD) is maximized due to CPT. This modulation frequency is controlled via an internal servo control loop to maintain CPT and becomes the reference clock frequency for the timing system. Atomic clocks need to be placed inside a magnetic shield to prevent any magnetic-field induced Zeeman splitting in the atomic absorption spectrum.

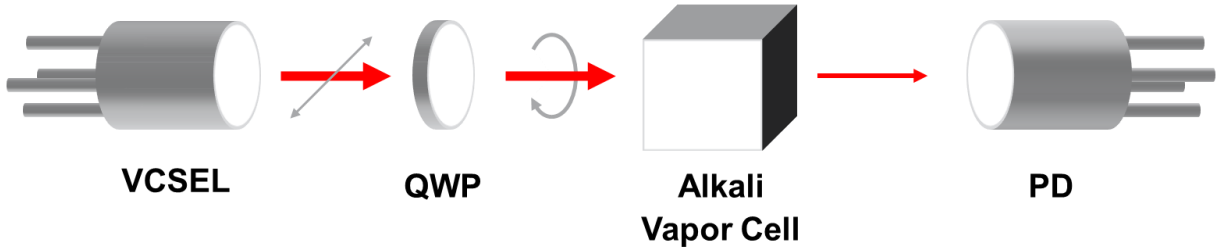

Figure 03: Atomic clock uses a polarized VCSEL and a QWP to deliver circularly polarized light into an alkali gas cell. A PD is used to monitor for increase in laser transmission during CPT.

The two required excitation frequencies can be generated through the modulating a single VCSEL source with a small, sinusoidal AC component with FM modulation on top of the DC bias current. The result is the generation of equally spaced sidebands on both side of the fundamental emission wavelength and displaced by the modulating frequency ω_m. CPT is best targeted by maximizing the power in the first order (+1 / -1) side bands in the laser spectrum. By modulating at one-half of the hyperfine splitting while fine-tuning the laser to the fundamental absorption line, the atomic clock can generate two wavelength peaks aligned with the hyperfine spectral bands.

CPT is achieved by centering the VCSEL wavelength at the central absorption peak and applying an FM signal to the VCSEL forward current equal to the hyperfine line splitting frequency. The central operating wavelength of a VCSEL can be tuned by both changing the operating temperature and the forward DC bias current. Temperature control allows for a broad range of wavelength tuning, and bias current adjustments allows for a finer degree of tunability.

The FM modulation frequency required to induce CPT is then used to correct the timing of the output clock signal. The international standard definition of the second is 9,192,631,770 oscillation periods of the cesium hyperfine frequency. In a Cs-based atomic clock, a 4.6 GHz microwave source locked to the CPT yields a frequency that is exactly half of the cesium ground state hyperfine splitting. An atomic clock can alternatively be made using Rb when the microwave frequency is locked to its CPT resonance of 3.4 GHz.

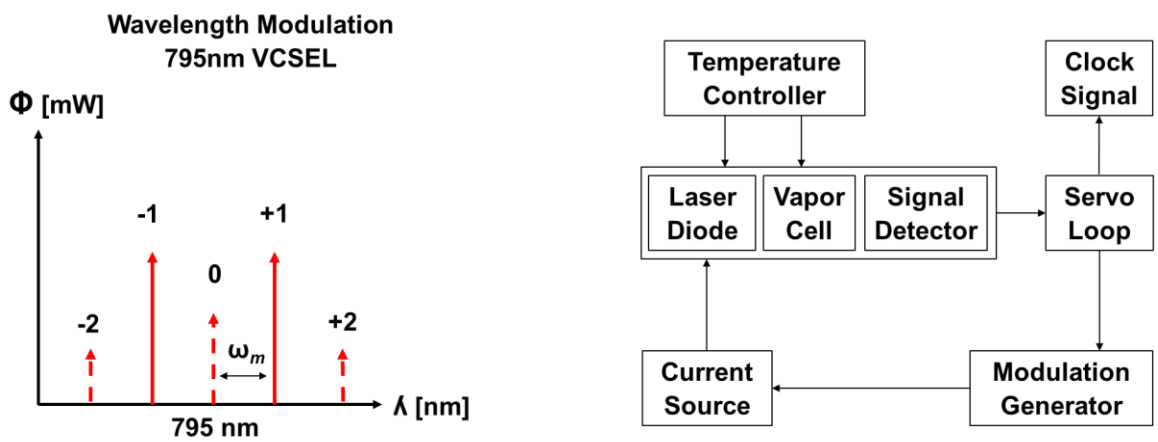

Figure 04: Frequency modulation (FM) of the VCSEL forward current results in mode splitting in the VCSEL wavelength spectrum (left). Circuit block diagram to control modulation frequency to hit CPT and output the reference clock signal (right).

3 VCSEL Characteristics

3.1 Singlemode Operation

A top-emitting VCSEL is an optoelectronic device that consist of quantum wells purposefully positioned between two Distributed Bragg Reflectors (DBRs) with the bottom DBR designed with 100% reflectivity. The DBRs are repeating layers of dielectric material with thicknesses on the order of a quarter of the operating wavelength, and the number of repeating units correlate to the effective reflectivity of the DBR. The DBRs also create a Fabry-Perot cavity and ultimately determine the operating wavelength of the VCSEL.

To ensure for both electrical and optical confinement inside the VCSEL, an oxidation layer is grown and developed near the quantum wells. The final oxidation structure creates a short, cylindrical waveguide where the optical power is confined between the DBRs and the oxide aperture. The cavity length is only a few microns in length, so only one longitudinal mode is present and acts as a Fabry-Perot cavity. However, a large oxide aperture will support various transverse modes, and each transverse mode will emit at a slightly different wavelength. For atomic sensing VCSELs, a small oxide aperture of < 6 microns is required to only excite the fundamental transverse mode and create a narrow linewidth required for operation. Most atomic sensing applications require a 20 dB difference in optical power between the fundamental mode and the sum of all other higher order modes.

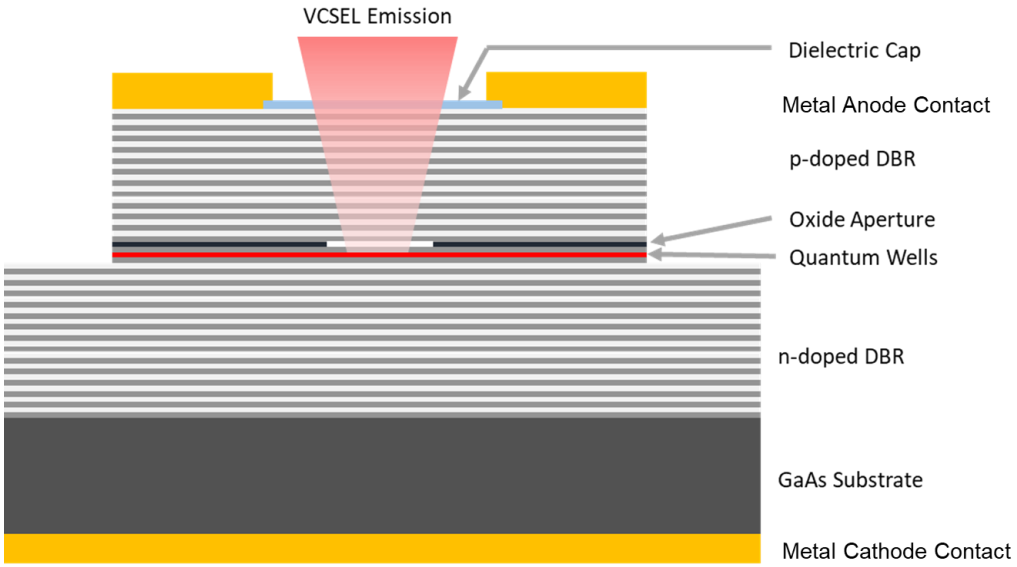

Figure 05: Illustration of a cross-section of the VCSEL aperture.

Singlemode operation is limited to a certain forward current range. Higher current densities push more charge outside of the confinement layer. In addition, thermal lensing and spatial hole burning alters the waveguiding properties of the VCSEL. Both phenomena will increase the excitation of unwanted higher order modes and will degrade the beam quality and spectrum of the VCSEL. The presence of multimode excitation is observed as two peaks in the wavelength spectrum. Thus, VCSELs for atomic sensors are limited to forward currents of < 1.5 mA. Regardless, this parameter will vary with different operating environments and should be tested thoroughly by the end user.

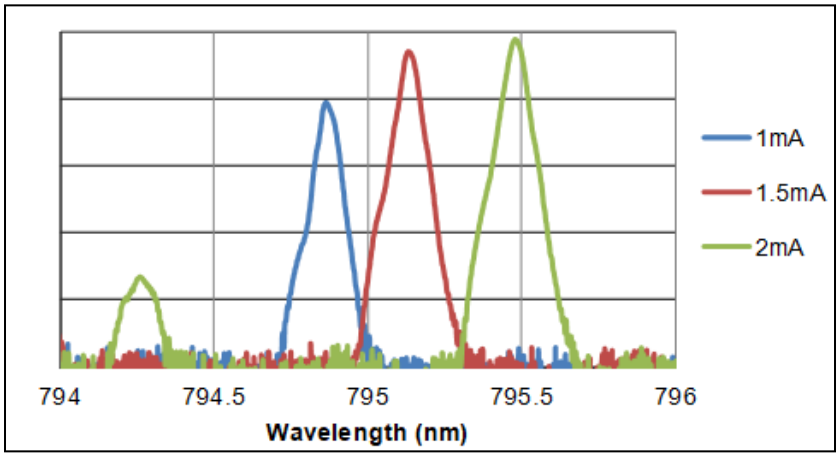

Figure 06: Wavelength Spectrum of a singlemode VCSEL. A second mode is excited when driven at 2 mA, as observed by the presence of a second peak in the output spectrum.

3.2 Wavelength Stabilization

While most commercial VCSELs have a top DBR designed for maximum output efficiency, VCSELs designed for atomic sensors are designed to decrease the spectral width of the signal to better target atomic excitation lines. While this design reduced the maximum singlemode power produced, atomic clocks applications don't require more than a 100 µW of power. A narrower linewidth is more important for atomic sensing applications to better detect atomic energy levels.

To stabilize the VCSEL wavelength to within the target's atomic linewidth, the temperature needs to be adjusted and stabilized to within a few millidegrees. VCSELs for atomic sensors exhibit a wavelength tuning coefficient of 0.055 nm/°C (795 nm) and 0.060 nm/°C (895 nm). For most applications, a wavelength-binned VCSEL is selected to operate optimally at a specified ambient temperature (> 60 °C) at which the atomic sensor is thermally controlled. The module can be heated and stabilized with traditional electrical heating elements to the desired operating temperature to hit the target wavelength. Alternatively, designs can incorporate a thermoelectric cooler (TEC) to fine-tune the operating temperature of the VCSEL.

The VCSEL wavelength can also be fine-tuned with forward current. However, this method of wavelength tunability is only available in a limited range for atomic sensing applications. There is a minimum current required above threshold current to create enough optical power for atomic sensing, and the VCSEL will start to excite higher-order modes when driven at higher forward currents. VCSELs for atomic sensors typically experience a current tuning coefficient of typical 0.4 nm/mA (795 nm) and 0.5 nm/mA (895 nm).

3.3 Polarization Control

Standard VCSELs commercially available do not exhibit linearly polarized light. While each mode inside the VCSEL will be polarized, the polarization angle will randomly be either parallel or perpendicular to the wafer's crystal axis. Due to the circularly symmetry of the VCSEL aperture, the polarization will also unexpectedly flip between polarization states spontaneously with minimal influence from current or temperature fluctuations. With higher order mode excitation, the final output beam is a summation of each mode's polarization properties.

Linear polarization is important for atomic sensors for the quarter-wave plate to produce circularly polarized light necessary to achieve CPT. To ensure polarization stability, Vixar's atomic sensor VCSELs are designed with a lithographically patterned surface relief grating. The surface grating acts as linear polarization lock by implementing a higher optical cavity gain in the targeted polarization direction. Grating performance is strongly dependent on both grating shape and etch depth. The surface grating is designed to optimize the polarization stability and maximize output power. The polarization lock also acts as a grating and must be designed to minimize the power in higher order grating modes. Production results have shown that this design exhibits high polarization extinction ratios (PER) greater than 15dB.

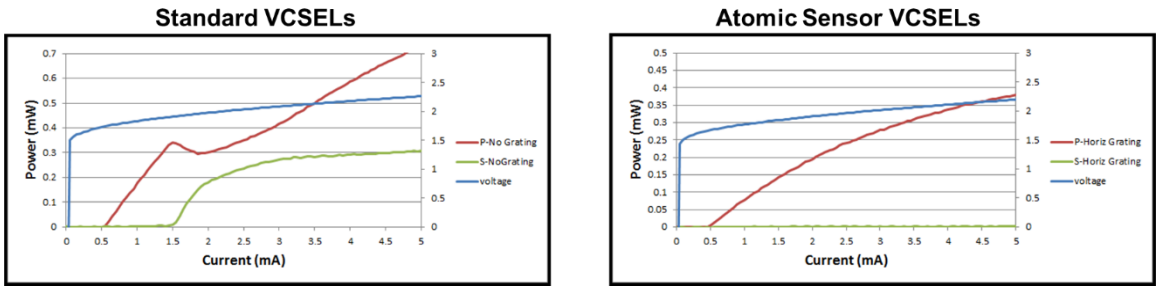

Figure 08: Traditional VCSELs exhibit poor polarization stability (left). VCSELs designed for atomic sensors are fabricated with a polarization lock to ensure a high PER (right).

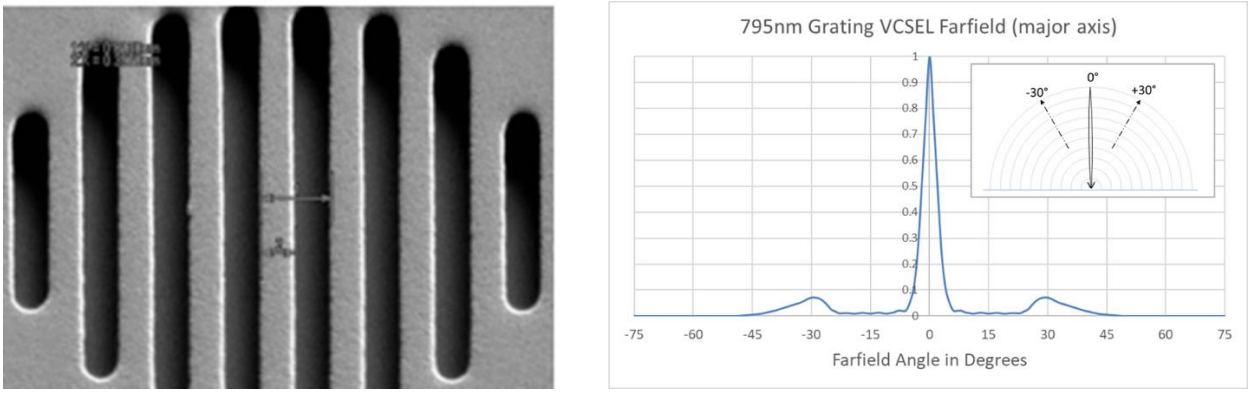

Figure 07: SEM image of the polarization grating on a VCSEL (left). Angular beam profile measurement showing minimal power in higher order diffraction modes (right).

4 VCSEL Production

4.1 VCSEL Wafer Probe Testing

The performance of atomic sensor VCSELs is sensitive to many factors including manufacturing variation typical in epi growth and die fabrication. Due to the VCSEL's high sensitivity to these factors, all VCSELs for atomic sensors from Vixar are 100% tested for LIV, wavelength, and polarization characteristics. This ensures that the product meets the customer requirements when delivering higher volume shipments. This information is also correlated to expected performance of each VCSEL at binned operating temperatures.

4.2 VCSEL Qualification

VCSEL wafers are run through qualification testing to verify that the die performance meets additional criteria. Vixar samples production wafers for qualification and reliability testing. Vixar conducts High Temperature Operating Life (105°C, 4mA and 125°C, 4mA) and High Humidity High Temperature (85°C, 85%, 1.5mA) testing in accelerated conditions to ensure lifetime dependability for chip scale atomic clock applications.

A small subset of VCSELs are picked off the fabricated wafer and tested for specialized criteria including spectral characteristics, sideband asymmetry, signal noise, and beam divergence. VCSEL samples are tested to verify linewidths of < 50 MHz (spectral widths of ~0.1 pm). VCSELs are tested for Sideband Asymmetry (SBA) to confirm relatively equal power splitting between the first order (+1 / -1) sidebands during wavelength modulation. Vixar also measures the VCSEL's relative intensity noise (RIN) to ensure unwanted power fluctuations are not present in the optical signal.

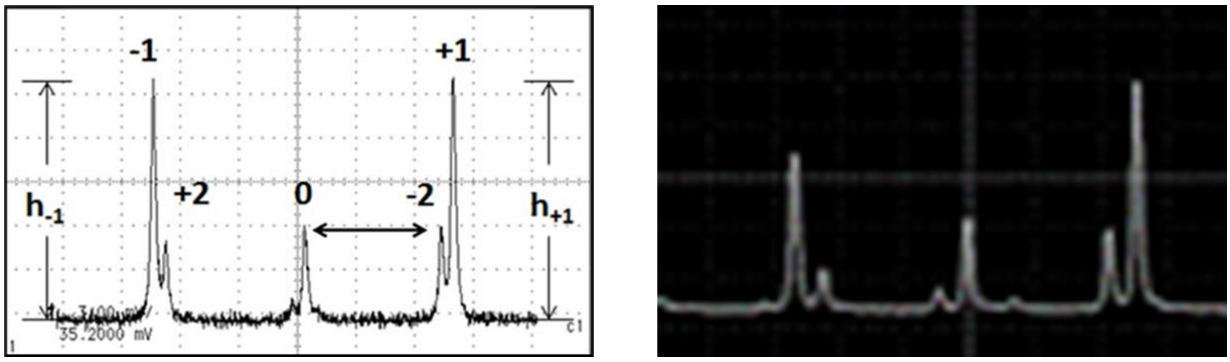

Figure 08: VCSEL spectrum measurements showing mode splitting with no SBA (left) and minor SBA (right) present in a VCSEL's spectrum during FM modulation.

4.3 Wavelength Binning

For mass production, most VCSELs on a fabricated wafer will experience a range of emission wavelengths at room temperature. In addition, the mean laser wavelength per wafer will drift between growth batches. Thus, the lasing wavelength of VCSELs on a fabricated wafer can deviate by over ± 10 nm from the epi growth's wavelength target.

To improve linewidth targeting for atomic sensing, Vixar bins its 795 nm and 895 nm singlemode VCSELs into operating wavelength groups. VCSEL die are probed at 85°C and sorted into groups with a ± 0.5 nm wavelength range. This ensures binned VCSELs will hit the target Rb and Cs wavelengths within a ±10°C operating temperature window. This effort minimizes the thermal tuning range an atomic clock manufacturer needs to control before achieving CPT.

The absorption lines of Rb (795 nm) and Cs (895 nm) are the most important wavelengths for atomic clocks. The wavelength shift over temperature can be used to determine the VCSEL's vacuum peak wavelength under different operating temperatures. Wavelength binning can also be determined for either open air or vacuum packaging. Vixar bins its VCSEL for atomic sensors into 5 groups that hit these atomic linewidths at different operating temperatures between 60°C to 100°C.

VCSEL Binning:	Operating Mode:
Group 1	T_a = 60±10°C
Group 2	T_a = 70±10°C
Group 3	T_a = 80±10°C
Group 4	T_a = 90±10°C
Group 5	T_a = 100±10°C

Figure 09: Vixar's operating temperature binning available for its atomic sensing VCSELs.

5 Atomic Sensor Die Packaging

The die attach process can affect the VCSEL's performance, including the laser's operational wavelength and polarization. Higher temperatures and/or faster cure times induce mechanical stress that may affect the VCSEL polarization and wavelength. When bonding VCSEL die for atomic sensors, Vixar recommends using silver epoxy designed to be cured at low (<100°C) temperatures for long curing durations. The mounting surface of the VCSEL could also induce die stress. The thermal expansion mismatch between the die and substrate will also transfer stress to the die and may affect its performance over temperature. The coefficient of thermal expansion (CTE) of bonding materials and substrates should both be taken into consideration when bonding atomic sensor VCSELs.

Hermetic sealing is important due to the wavelength sensitivity of the ambient gas present at the VCSEL window. One way to better control the wavelength of the VCSEL is to package the die in a TO can. The TO can package is a proven solution that is robust and best maintains the optical properties of the packaged VCSEL. The TO can window should be coated with an anti-reflection (AR) coating to reduce any optical feedback back into the VCSEL cavity and improve signal SNR.

The ambient gas inside the package will determine the final wavelength of the VCSEL. The refractive index of the ambient inside the package affects the wavelength tunability of the top DBR and shifts the operating wavelength of the VCSEL. This change is measurable when the VCSEL is enclosed in either air or in a vacuum. VCSELs in a vacuum typically demonstrate a wavelength 0.2 nm longer than when operated under air at atmospheric pressure.

Die encapsulation cannot be used to cover the VCSEL for any atomic sensing applications. Significant shifts and variances of the expected wavelength are observed with any form of encapsulation. In addition, die encapsulation will negate the effect of the polarization lock, and the VCSEL's polarization will no longer be stabilized.

After packaging, module burn-in is recommended once the die is completely packaged. VCSEL parameters will slightly shift and swing during the early stage of its lifetime, which can affect the atomic sensor's performance. A burn-in procedure, which involves driving the VCSEL at high currents and temperatures, will anneal the VCSEL layers inside the semiconductor die. Burn-in is recommended by the end user until stability in VCSEL performance is observed. Vixar recommends a burn in of 24 hours under continuous wave operations (3mA) at room temperature.

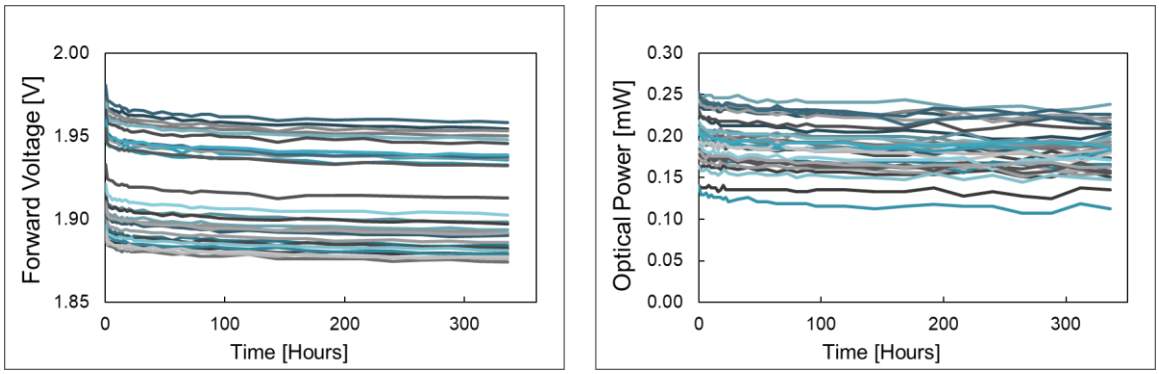

Figure 09: Atomic sensor VCSEL modules undergoing burn-in, with the driving conditions being 3mA at 100 °C for two weeks. VCSELs were monitored for output power (left) and voltage (right).

6 Conclusions

The design of VCSELs considers many important requirements for effective atomic sensing. VCSELs need to be single-mode, polarization stable, and have a narrow linewidth. In addition, VCSELs for atomic sensors need to perform with low intensity noise, minimal asymmetry, and high modulation frequencies.

Vixar designs the fabrication of VCSELs for atomic sensors around these requirements and verifies the performance through rigorous testing and verification. Die are 100% tested for LIV performance and polarization stability, and wafers are qualified with tests essential for atomic sensing.

Atomic sensor VCSELs are designed and binned to deliver high wavelength accuracy for atomic spectrum measurements. VCSEL packaging must also be planned to minimize any production issues and ensure optimally performing atomic sensors.