VCSELS FOR RUBIDIUM D1 (795 NM)

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Abstract

Vertical Cavity Surface Emitting Lasers (VCSELs) are an enabling technology for miniature atomic devices, including clocks. As VCSELs age, their optical properties vary, introducing timing errors including light shifts and frequency drift. Shorter wavelength VCSELs, such as those used to probe atomic Rb (780 and 795 nm), have been less studied than those which operate at the longer wavelengths used for communications or to probe Cs (852 and 895 nm). It is thus of interest to examine the performance of shorter wavelength VCSELs. In this paper, we survey 795 nm VCSELs supplied by a commercial vendor and evaluate wavelength drift, power drift, and polarization stability, in consideration of requirements for clock stability.

INTRODUCTION

Miniature atomic clocks enable communications and navigation technologies that would not be practical with larger, heavier, higher power, or less accurate frequency standards. They are more economical to boost into space, are man-portable, and draw minimal power so that they can run for long time periods on small batteries. They can be packaged protectively to operate in harsh environments, and the potential for mass-manufacturing means they can be deployed in large numbers in cost-sensitive products. Like traditional atomic clocks and other atomic sensors, however, they rely on a narrow-band light source for optical pumping and for read-out of the atomic states. **[1,2]**

Vertical Cavity Surface Emitting Lasers (VCSELs) have proven to be ideal for this purpose. Their minimal size and power consumption is consistent with the goals of miniature atomic clock design, and their widespread use in other applications means that they are already a well-developed, low-cost technology. They can be made single-mode with well-defined polarizations and linewidths on the order of 10 MHz at wavelengths appropriate for alkali-based atomic clocks. Most commerical off-the-shelf VCSELs, however, have been developed for communications and optical sensing and readout applications, and do not meet these atomic-device specific requirements.

Atomic clocks, in particular, have even stricter requirements than some other atomic sensors: for clocks it is most critical that the properties of a VCSEL be stable over time, since changes in the VCSEL power, wavelength, and polarization can shift the clock frequency or introduce noise **[3]**. VCSEL power instability causes a time-varying Stark shift in the atomic states of clock **[4,5]** and the signal-to-noise level of the frequency measurement. Polarization variation also affects the signal-to-noise level, since improperly polarized light contributes to the noise without contributing to the signal. Wavelength drift changes the sensitivity of the clock states to power variations (since the light shift depends on both intensity and detuning) **[6]** and also changes signal to noise, since the background absorption and contrast

change with wavelength. If any of these properties drifts significantly relative to the compliance limits of the electronic control systems, the clock signal is degraded.
Finally, VCSEL stability depends not only on fundamental characteristics resulting from growth, but also on assembly and control processes. This includes the stability of the current supply, the stability and phase noise of the VCO that modulates the VCSEL, the degree of isolation from ambient temperature variation, the stability of the wavelength control loop, and stress in the mechanical attachment, as we describe further below. It is these system level limitations that determine how much fundamental variation is acceptable in the VCSEL diode.

Here we report on the stability of these properties for VCSELs obtained from a commercial supplier, and analyze the causes of the variation we measure. The costs associated with fabrication, assembly, and especially long timescale testing of the VCSEL subassembly, add up to a significant fraction (historically up to 40%) of the cost of assembling a complete chip scale atomic clock. We have been successful in reducing assembly costs through fully automated assembly, populating over 150 VCSEL scaffolds to date with nearly 100% yield for electrical operation of VCSEL, heater, and thermal bridge. Nevertheless, a significant post-assembly yield reduction occurs primarily as a result of wavelength drift measurements, which require the temperature stability provided by the VCSEL scaffold. Taking a yield reduction following several assembly steps is clearly more costly than rejecting VCSELs based on pre-assembly screening performed at the VCSEL wafer level. For this reason, we also report here on correlations between pre-assembly and post-assembly measurements, suggesting low-cost screening procedures that could significantly improve post-assembly yield.

STABILITY REQUIREMENTS

VCSEL polarization is generally uncontrolled at the system level, requiring the diode to be intrinsically polarization-stable, and mounted in a mechanically stable way. Typical single-mode VCSELS for atomic clocks produce linearly polarized light through deliberately introduced strain in the material along one axis. This introduces a bi-refringence which causes the light polarized parallel and perpendicular to the strain axis to experience different optical path lengths. These two different cavity lengths correspond to two different resonant frequencies, one of which will be closer to the gain center than the other. The output will be single mode and linearly polarized when only the mode nearest the gain center is above threshold **[7]**.It is possible for the laser to mode hop from one polarization to the other if the gain peak or cavity resonance shifts, and it is possible for the laser to sustain both modes if the gain is sufficiently high. The dynamics of these polarization flips are complex **[8]**. The empirical question we want to address regarding polarization is whether these flips can be eliminated by proper design and mounting, or whether VCSELS need to be screened optically for polarization stability before assembly into clocks.

The question is different for power and wavelength. In real clock operation, servo systems feed back to heaters and current sources for the VCSEL to maintain the optical power and wavelength at constant values.

If the VCSEL diode does not age or otherwise vary significantly over time, this can be achieved by keeping the operating temperature and VCSEL current themselves constant. The VCSEL consists of an active region (p-n junction) with Bragg reflectors on either side (Fig. 1). The Bragg reflectors form an optical cavity, and the round-trip optical path length of this cavity determines the laser frequency.

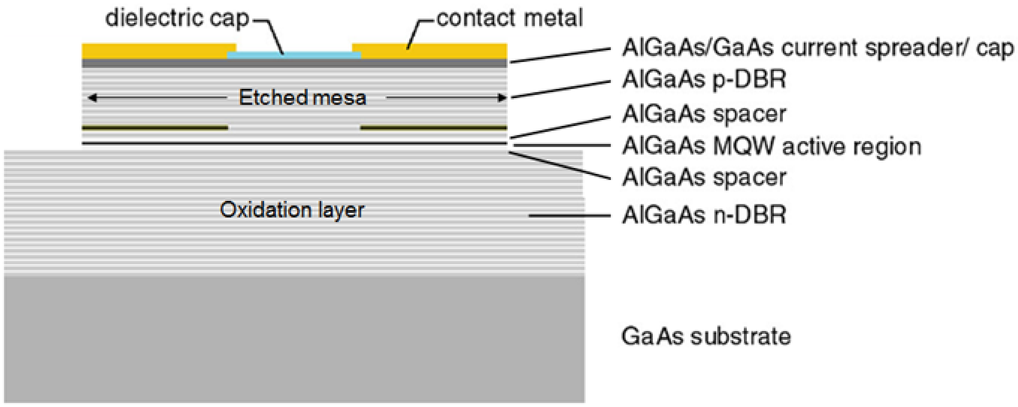

Figure 1. Fundamental structure of VCSEL fabricated from Gallium Arsenide (GaAs) with Aluminum Gallium Arsenide (AlGaAs) Distributed Bragg Gratings (DBR) and Multiple Quantum Well (MQW) active region. (Figure supplied by Vixar, used with permission.)

Since the material expands with temperature, changes in temperature alter the physical path length and thus the laser output frequency. Since optical path length is the product of physical path length and index of refraction, however, it can change even when the temperature remains constant. The index of refraction of the p-n junction is related to the optical gain of the junction by the Kramers-Kronig relations **[9]**. The result is that lasing frequency can be altered by anything which changes the gain profile, including both changes in current and changes in the bandgap energy or efficiency of the p-n junction due to aging. This coupling between the diode gain and lasing frequency is called "mode pulling" and is illustrated in Fig.2 **[10]**.

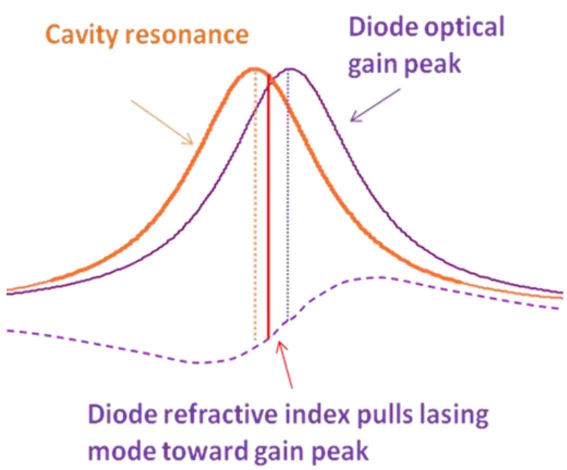

Figure 2. Example lineshapes for cavity resonance and optical gain vs. optical frequency. The lasing mode is "pulled" toward the gain peak frequency.

For real VCSELs, it is thus not possible to keep the VCSEL output power and wavelength constant over long time spans merely by keeping the input temperature and current constant. An ideal control system would measure the wavelength and power directly and feed back to the current and the temperature. However, even an ideal control system cannot provide completely satisfactory control over an unstable VCSEL. First, the feedback loops are necessarily coupled since both inputs affect both outputs, and the dynamics of these coupled loops can introduce noise on shorter timescales. Further, the compliance limits of the feedback set upper limits on the lifetime: once the power or current drifts too far, the control systems can no longer correct them. In many implementations the compliance limits and the resolution of the feedback are also coupled, so that choosing higher limits to extend lifetime increases noise at short time scales. All of these effects are mitigated, however, if the intrinsic properties of the diode are chosen to maximize stability over time. Once an operating point has been found, which is a current and temperature that give acceptable optical power and wavelength, it is the aging of the diode which sets the long term rate of change of that operating point, and determines the demands on the control systems. For this reason it is important to characterize the stability of the diodes themselves, and to apply this information in screening and quality control strategies for atomic clock manufacturing.

Using conventional methods, however, this type of screening can add significantly to manufacturing costs. Wavelength and power drift are optical measurements requiring each VCSEL die to be mounted with current and temperature control systems and the output directed onto a photodetector. Previously, a significant fraction of VCSELs were rejected on the basis of these measurements, particularly for excessive wavelength drift. Rejections at this point in the process mean that the rest of the assembly must be scrapped even if all other parts are good. Reworking the assembly with a new VCSEL is even more expensive, since this is a manual task. For wavelength testing, extensive set-up is required to couple the VCSEL output into a wavelength discriminant such as an interferometer, grating, cavity, or gas cell. On the other hand, if some kind of correlation can be established between these optical properties, and properties that can be measured electrically with wafer or die-level probing, those electrical tests might be substituted for the optical tests. In this case VCSELs could be screened prior to assembly, no assemblies would have to be scrapped or reworked, and high performance and long lifetime assured at low cost.

EXPERIMENTAL RESULTS

WAFER LEVEL PROBE DATA

The first goal of this section is to demonstrate, based on both pre- and post-assembly test results, the limitations of wafer-level, pre-assembly screening. The second goal of this section is to show that VCSELs that meet the stringent requirements of atomic clock applications can be produced at relatively high yields, which means that such a wafer-level screening protocol need not be perfect: larger wafer level yields make “false negative” rejections less expensive (since many other good parts remain) and make “false positive” choices for assembly less likely.

Some wafer level screening tests are already standard. A full wafer probe of electrical resistance and of light output vs. current and vs voltage (an “LIV” probe) allows non-functional die to be eliminated. Optics on the probe card used for this testing can couple light into a fiber, and out to an optical spectrum analyzer to measure lasing wavelength. The wafer is heated to the desired operating temperature by external heaters during this measurement. Yield at this stage is typically high, as shown in Fig. 3.

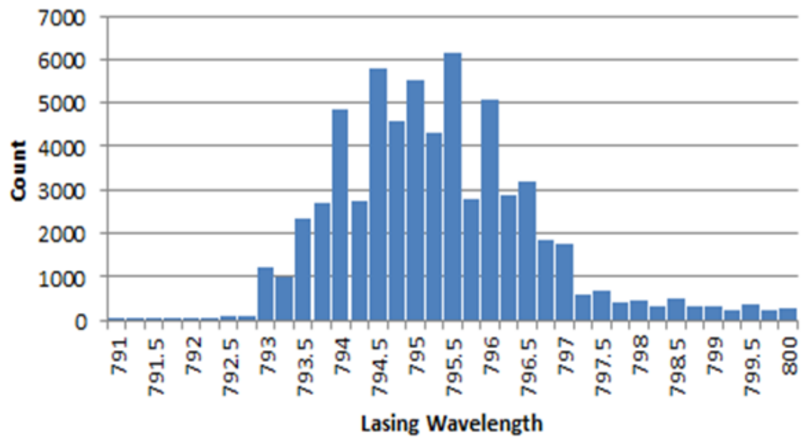

Figure 3. Histogram of actual lasing wavelengths at 85 C, target wavelength = 795nm. (Data supplied by Vixar, used with permission.)

Honeywell's CSAC design allows independent control of VCSEL and vapor cell temperatures, resulting in a wide acceptance range around the peak lasing wavelength shown in Fig. 3. It is therefore conceivable that, at low rate initial production quantities ~20,000 per year, an entire year's worth of CSAC production could be supported by a single wafer of VCSELs. At present, however, yield is reduced significantly by wavelength stability. Worse, screening for wavelength stability is costly, because automated the wafer level probe cannot be used to establish wavelength stability unless a means is found for continuously, rather than intermittently, energizing each VCSEL at constant current, while controlling the temperature of the entire wafer with great precision, ideally over several days. Such a setup is imaginable, but technically challenging.

Polarization measurements at this stage also allow VCSELs with significant polarization components orthogonal to the desired axis to be eliminated prior to assembly. We compared these polarization measurements to post-assembly polarization measurements and found good agreement for low-strain mounting configurations. The wafer-level data suggested a standard deviation of 5.2 degrees for operating currents of 1mA. Sample post-assembly data is shown in Fig. 4.

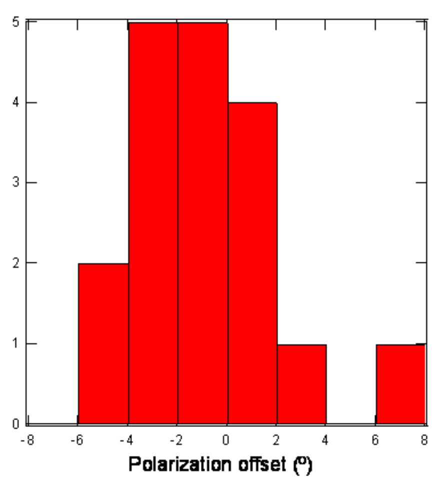

Figure 4. Histogram of polarization offset angles for mounted VCSELs.

With low-strain mounting, the polarization was found to be stable over time at constant current. Polarization flips can occur repeatably as function of current at critical points unique to each device. In clock operation, the current will be adjusted by servo systems to maintain constant wavelength and power. A screening protocol which identifies polarization flips as a function of current and eliminates die for which the flips occur at currents near the planned operating point can then be used to predict which devices will be stable over time. This screening can be performed at the wafer level.

The light level as a function of time for constant voltage can also be tracked at the wafer level. VCSEL power levels generally vary more during approximately the first 100 hours of operation, with the rate of change slowing down after this "burn in" period, as illustrated in Fig. 5.

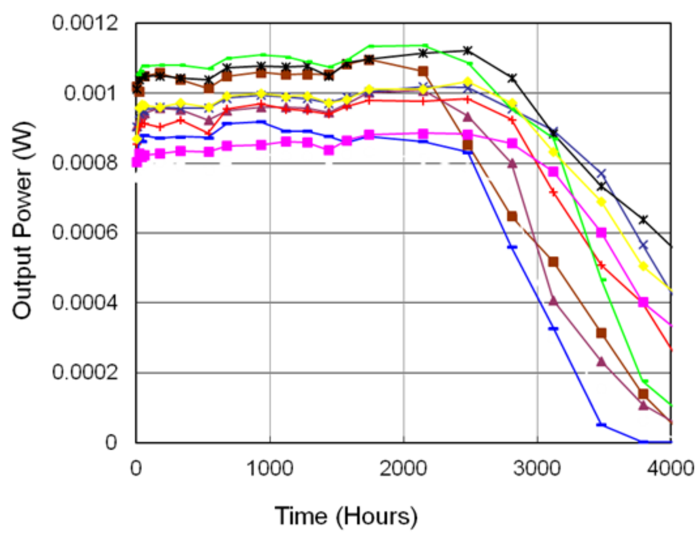

Figure 5. Optical power output as a function of time for 10 VCSELs under accelerated aging conditions. (Data supplied by Vixar, used with permission.)

Under accelerated aging conditions (85 C platform temperature, 5 mA junction current), VCSEL lifetime is approximately 2500 hours. For operation at 1.0 mA and 85C, lifetime is increased by a factor of approximately 140, which accounts for the reduced current flow, as well as the decrease in junction temperature at reduced current. This indicates a lifetime for continuous operation at 1.0 mA and 85 C of up to 40 years. This is consistent with data taken at lower currents with lower acceleration factors, predicting lifetimes greater than 30 years for operation at 1.0 mA and 85 C. Note that through the AC Stark effect and other factors, power variation shifts the clock frequency, with a long term fractional frequency shift well below 1E-11/hour for the parameters listed above. Initial aging of the VCSEL causes larger shifts, necessitating a burn-in period in which accelerated VCSEL aging allows stable operation to begin sooner.

Polarization angle, electrical resistance, optical power vs. current and voltage, and initial wavelength, then, represent the data which can be obtained at the wafer level. The next goal is to determine whether the short and long-term stability of the VCSELs can be predicted from any function of these measurable variables.

MEASUREMENTS ON ASSEMBLED VCSEL SCAFFOLDS

The results above can be obtained at the wafer level either by probing each die for a short period of time with an individual current and voltage, or (prior to die separation) wiring all the die in parallel and providing a common voltage, then collecting data over a long period of time. To provide each die with its own current and voltage one by one and then collect data over time for each becomes prohibitively time consuming. Nor are testers available with enough inputs and outputs to provide all of the (~100,000) die with their own power supplies simultaneously. Consequently, individual measurements of voltage vs. time at constant current are not done at the wafer level. They can, however, be performed during the "burn-in" stage of operation, mentioned above. We have developed a 10x batch ovenized burn-in capability and collected voltage and optical power output data for VCSELs during burn-in. The aging processes which cause variation in optical power with time are also reflected in a time variation of the voltage across the VCSEL at constant current, as shown in Fig. 6.

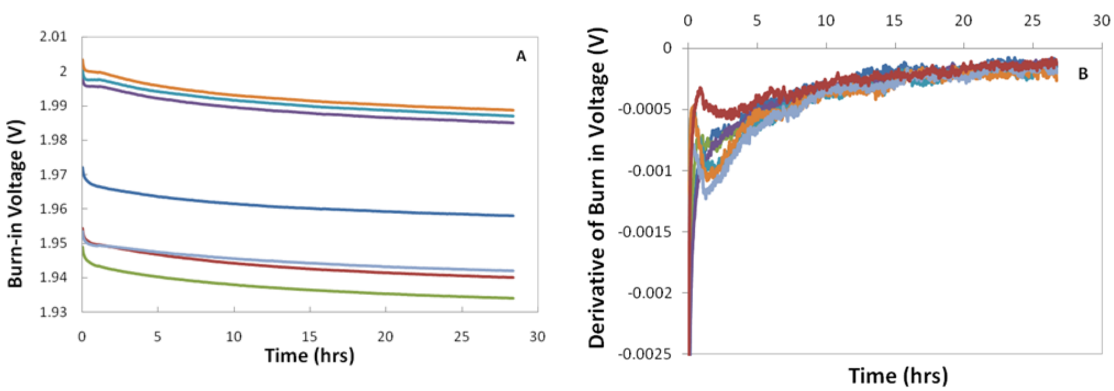

Figure 6. (a) VCSEL voltage at constant current as a function of time during burn-in period for 7 devices. (b) Rate of change of VCSEL voltage at constant current vs. time during burn-in period (filtered through 0.6 Hz cut off low pass filter).

One initial hypothesis was that long term wavelength stability could be predicted from the final slope of this electrical burn-in curve, on the theory that if common aging processes are responsible for both types of variation they would co-vary, allowing an electrical property to be used as a proxy for an optical one. To test this hypothesis, temperature and current-controlled VCSELs were coupled into optical fibers, and an 8x1 fiber-coupled optical switch was used to sample data for up to 8 VSCELs at a time with a fiber-coupled wavemeter. The average wavelength drift rate was compared to the final slope of the voltage burn-in curve. No statistically significant correlation was, in fact, found between the burn-in voltage slope and the wavelength drift rate.

We note that the burn-in voltage versus time traces in Fig. 6(a) are noticeably displaced from one another on the voltage scale. This led us to a new hypothesis: higher resistance devices drift more than lower resistance devices. Since all of these VCSELs were powered with the same current, the instantaneous voltage serves as a measure of the resistance of the diode. Indeed, a statistically significant correlation was found between instantaneous operating voltage and wavelength drift, as shown in Fig. 7(a).

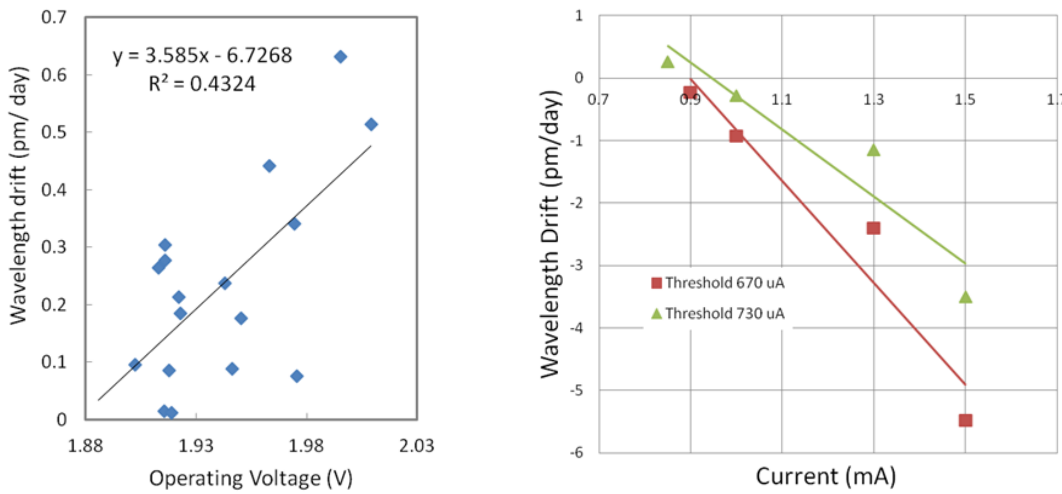

Figure 7. (a) Wavelength drift rate in picometers per day vs. operating voltage, for a fixed current. (b) Wavelength drift rate in picometers per day vs. operating current.

It is likely that higher resistance VCSELs have smaller apertures and therefore higher current density in the gain region, potentially promoting electromigration of the aluminum dopant in the quantum wells, and shifting bandgap, and thus varying the refractive index and the lasing wavelength. If elevated current density is a factor in causing accelerated wavelength drift, then one would expect a correlation between absolute operating current and wavelength drift rate as well. Fig. 7(b) shows just such a correlation, strongly supporting this hypothesis.

Devices with larger apertures (and lower resistance) are somewhat less likely to be single-mode. Note that the curve with the lower threshold current is offset to the left, meaning higher drift. In general higher drift also correlates with lower threshold current, which supports the notion that drift is associated with small apertures. This screening should therefore be accompanied by measurements on each device to verify that it is single mode. Currently, the fidelity of single mode behavior is inferred from wafer level OSA data, and therefore adds no cost.

CONCLUSIONS

We find that wafer level tests yield measurements which correlate significantly with the stability of VCSEL wavelength, intensity, and polarization over time. Voltage vs. time curves measured at burn-in tend to co-vary with intensity vs. time measurments, but are not correlated with wavelength vs. time. Low device resistance before and after burn-in, and low operating current do correlate with greater wavelength stability. Finally, pre-assembly polarization agrees well with post-assembly polarization provided low-stress assembly techniques are used, and polarization that is stable as a function of current near the operating point is also stable over time. Our data also suggest that VCSEL wavelength drift, polarization stability and long term intensity stability can all be improved by operating at lower currents, closer to threshold. However, short term intensity stability may be increased by operating at lower temperature and must therefore be optimized against long term stability and lifetime.

With proper screening, VCSELs already on the market can meet the requirements for chip scale atomic clocks and other atomic devices. A single wafer can yield thousands of single-mode, narrow-linewidth lasers with the desired wavelength, intensity, and polarization at the desired operating temperature.

Currently we find ~50% of the die we screen, after selection based on wafer level data, meet all of our criteria for operating points and long term stability, with most rejections due to unacceptable wavelength drift. A number of vendors are already making similar devices at a range of optical powers, and the screening protocols suggested here can be applied to any of these parts.

Prior to the development of these screening protocols, the VCSEL was the single largest contribution to the overall cost of a CSAC. Adoption of these protocols is projected to reduce the cost of the VCSEL by 60%. Coupled with other improvements in MEMS processing, automated assembly and packaging, and a reduction in overall parts count, the projected CSAC cost in volume production is now consistent with our cost targets for commercialization.

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