SAND2011-0686C

Feedback in close-coupled axial VCSEL-photodiode pairs

Kent. M. Geib*[a], Darwin K. Serkland[a], Gregory M. Peake[a], and Victoria M. Sanchez[b]
[a]Sandia National Laboratories, 1515 Eubank SE, Albuquerque, NM, USA 87185-1085;
[b]LMATA Government Services, 4209 Balloon Park RD. NE, Albuquerque, NM, USA 87109-5802

ABSTRACT

We have been investigating the use of coaxial multimode VCSEL/PD (vertical cavity surface emitting laser/photodiode) pairs for positional sensing with emitter to target mirror distances on the order of 1mm. We have observed large variations in signal levels due to the strong optical feedback in these close-coupled systems, employing either heterogeneously integrated commercial components or our own monolithically integrated devices. The feedback effect is larger than anticipated due to the annular geometry of the photodetector. Even though there is very little change in the measured VCSEL total output power, the optical feedback induces variations in the transverse mode distributions in these multimode VCSELs. The higher order modes have a larger divergence angle resulting in changes in the reflected light power incident upon the active detector area for a large range of emitter/mirror separations. We will review the experimental details and provide strategies for avoiding these variations in detected power.

Keywords: VCSEL, heterointegration, optical feedback, resonant-cavity photodiode, optical position detection, proximity sensing

1. INTRODUCTION

We have been investigating the use of coaxial VCSEL/photodetector pairs for monitoring the position of a rotating gear which has a number of micromirror reflectors that indicate the wheel orientation, as depicted schematically in Fig. 1a. VCSELs are an ideal light source for this functionality due to their small size, directionality, high efficiency, and reliability. We have been studying both commercial VCSELs mounted on top of commercial silicon PIN photodiodes and our in-house fabricated monolithically integrated VCSEL/RCPD (resonant-cavity photodiode) devices shown in Fig. 1b. The coaxial device typically provides very nice location information with a good contrast ratio, however, we have sometimes experienced a higher than expected level of 'noise' in the photodiode signal when the mirror is above the VCSEL. In both types of devices we have occasionally observed greater than 20% variation in detected power. The causes and mitigation of this signal variation are the topic of this report.

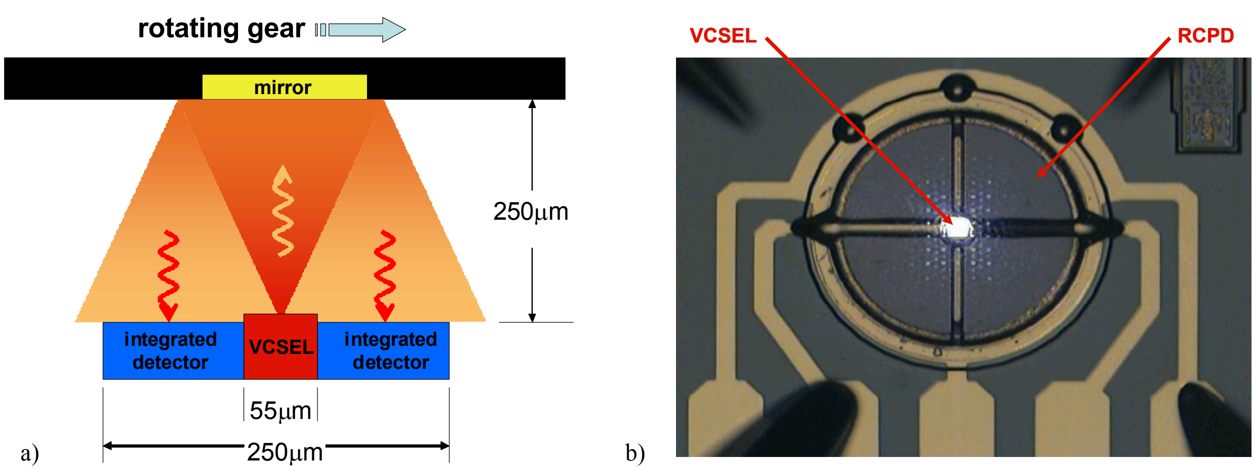


Figure 1a) Schematic of the optical position monitoring device b) Photomicrograph of the monolithically integrated device where the RCPD aperture diameter is 250µm.

*kmgeib@sandia.gov; phone 1 505 844-8214

2. THE EXPERIMENT

The basic optical test assembly shown in Fig. 2 was used to investigate feedback effects in the optical monitor device. All of the imaging components are anti-reflection coated and the OD1 filter is included to further reduce feedback effects that might arise from internal reflections within the collection optics. The NA=0.3 aspheric lens is fast enough to collect all of the light from the VCSEL for transfer into a monochrometer. The feedback mirror and OD filter are mounted in a tip-tilt stage which is attached to a piezoelectric translator. Maximizing the signal level on the RCPD at a constant VCSEL output and a 3mm sample to mirror separation can be used to make the mirror parallel to the device. We then drive the piezo to move the mirror in and out by a few micrometers to provide varying feedback phase while observing the RCPD current and VCSEL light output power with a constant VCSEL drive current. The piezo can be moved with a DC voltage to adjust the RCPD signal to a low or high state that is relatively stable but easily affected by air currents, floor vibrations and temperature shifts. It is much easier to determine the phase dependent feedback effects if we use an AC voltage on the piezo and observe the time varying signals on an oscilloscope.

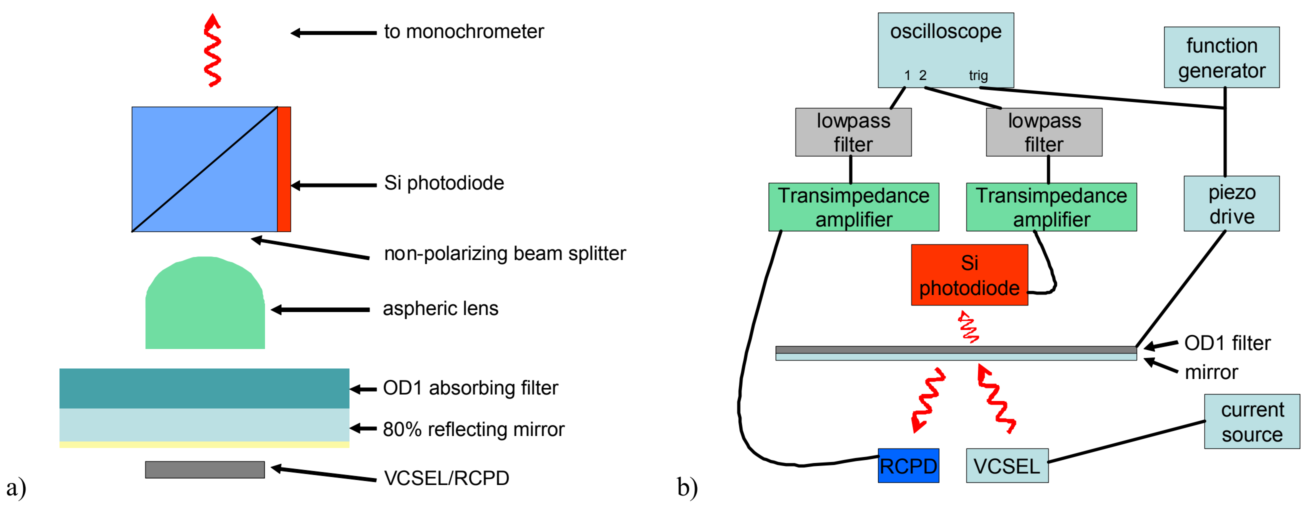
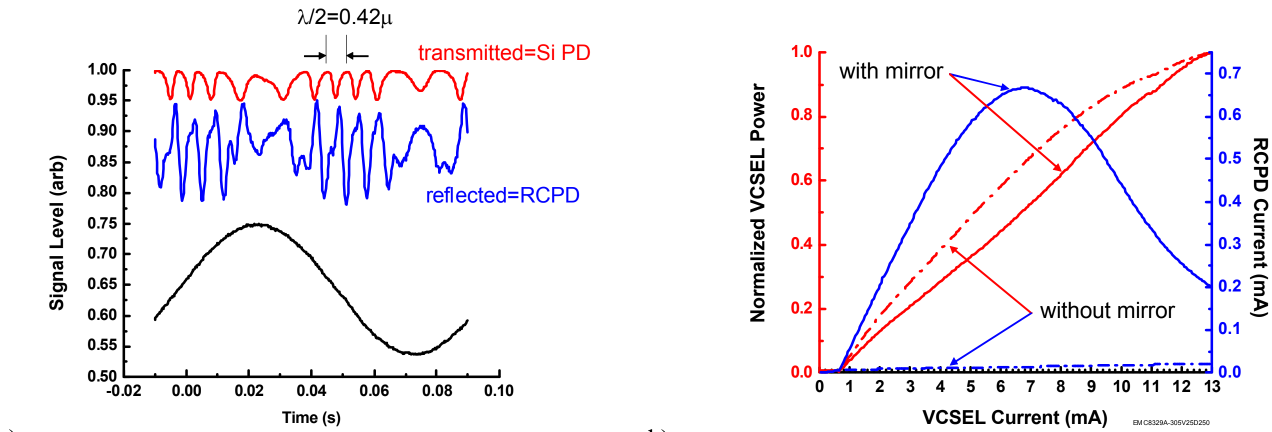


Figure 2. a) Schematic of the optical test system where the mirror and OD filter are mounted on a piezoelectric translator stage. b) Schematic of the basic electrical test setup.

In the following experiments, the piezo is driven with a relatively slow 10Hz sinusoid due to the mass of the 1-inch diameter optical components. The lowpass electrical filters are used to clean up the observed low voltage signals.

The device under test is a monolithically integrated VCSEL/RCPD pair which happens to show strong feedback effects making it a straight forward data set to analyze. The integrated device used to obtain this data contains a 5µm diameter oxide confined[1] VCSEL emitting at 850nm with a 21 pair top distributed Bragg reflector (DBR) and a 36 pair lower DBR. The 250µm aperture RCPD is formed by removing 1/4λ (~60nm) from the top DBR thereby reducing the cavity Q and broadening the photoresponse wavelength window. A plot of the laser output and the RCPD signal with and without a mirror is shown in Fig. 3b. The observed RCPD signal without a mirror results from the spontaneous emission that propagates laterally from the laser into the surrounding detector. The rollover in the reflected RCPD signal with increasing VCSEL output results from the VCSEL output wavelength shifting out of the 3nm full-width half-maximum RCPD response window due to current heating in the VCSEL. The RCPD could be further optimized at the expense of added complexity.[2]

Figure 3a presents an oscilloscope trace showing how the piezo movement relates to the observed signal at the device RCPD (feedback effects) and how the VCSEL output power (measured at the beam splitter) is affected. (The data has been normalized to place it all on the same plot.)



a) b)

Figure 3. a) Normalized oscilloscope traces showing the response of the transmitted (VCSEL output) and the reflected (RCPD photocurrent) signals to piezo motion (feedback phase). b) Transmitted VCSEL output power and measured RCPD signal verses VCSEL drive current with and without the 80% mirror in place. The RCPD signal without the mirror indicates the level of spontaneous emission coupling internally from the VCSEL to the RCPD.

The observed signal levels for several VCSEL drive currents are shown in Fig. 4 for a VCSEL to mirror separation of 250µm. A clearer picture of the magnitude of the feedback effect is obtained by plotting the signals as a percentage of the output power level. (In the case of our monolithically integrated device, there is a below-threshold spontaneous emission signal that is laterally coupled from the VCSEL to the RCPD, which is subtracted from all RCPD signals before normalization.) This percentage data is plotted in Fig. 5a where we see a significant difference in the amount of signal variation between the transmitted and reflected signals. Using the same percentage analysis and plotting the maximum peak-to-peak variation of the reflected and transmitted signals we can see how they vary with VCSEL drive current in Fig. 5b. The reflected RCPD variation is always larger than the transmitted VCSEL variation indicating that something other than simple VCSEL output power level variation must be occurring as the feedback phase is varied.

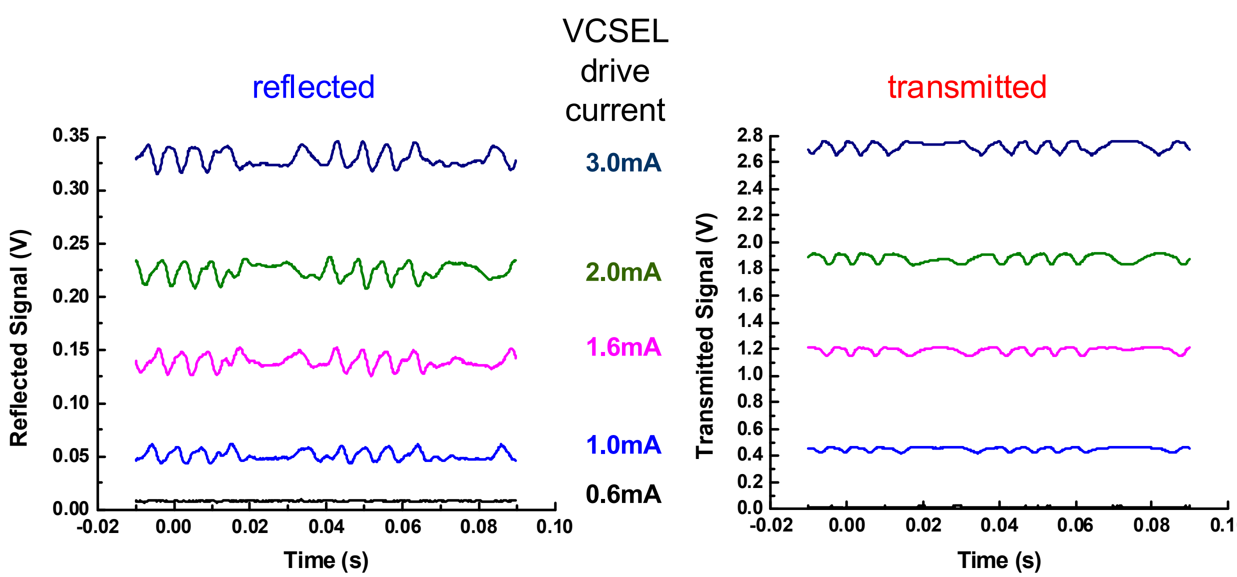
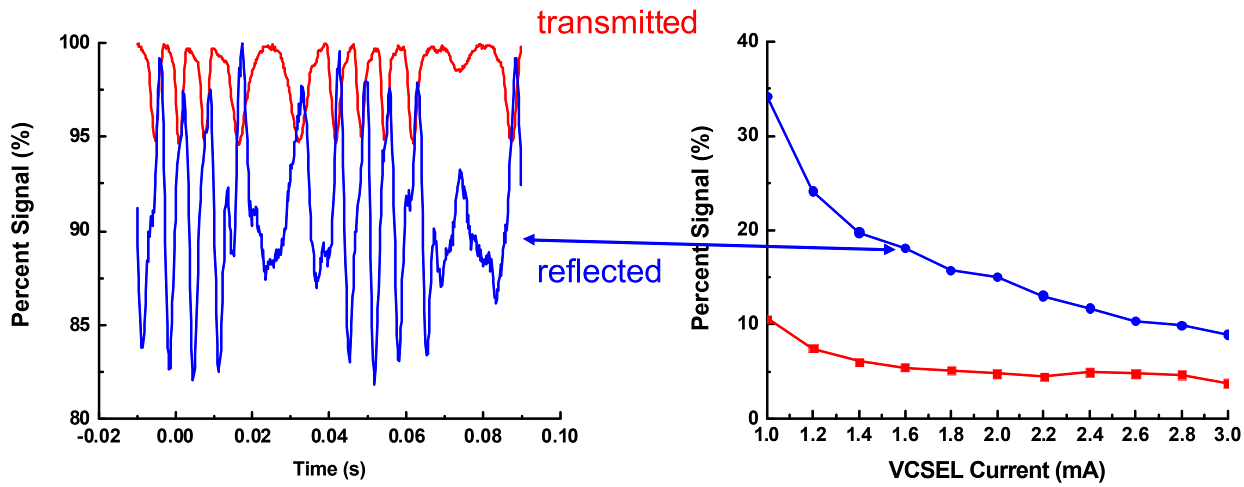


Figure 4. Observed oscilloscope traces for reflected RCPD photocurrent and transmitted VCSEL output for several VCSEL drive currents with the 80% reflecting mirror positioned 250µm from the VCSEL. (Note that the VCSEL operates below lasing threshold when driven at 0.6mA as seen in Fig. 3b.)



a) b)

Figure 5. a) Data from the 1.6mA drive current in figure 4 plotted as a percentage of the maximum signal level. b) Peak-to-peak percentage variation in the transmitted (red) and reflected (blue) signals for a 250µm device to mirror (R=80%) separation as a function of VCSEL drive current.

3. DISCUSSION

We see relatively small variations in the total VCSEL transmitted power due to feedback from the external mirror indicating that the large variation in RCPD detected power is likely related to power fluctuations between different transverse optical modes in the VCSEL cavity. Replacing the 10Hz AC signal on the piezo stage with a DC voltage, we adjust the feedback phase to obtain relatively stable operation in either the high or low RCPD signal level condition. Directly observing the far field patterns on a video camera for the two feedback states showed little change in the mode profile of the beam. However, by passing the transmitted light through a ½ meter monochrometer with a 1200g/mm grating and 260µm slits, we can spectrally separate the optical modes and determine what is occurring. The collecting aspheric lens is adjusted to focus the VCSEL output at the entrance slit of the monochrometer and a camera is placed at ~50mm from the output slit to provide a spectrally-resolved far-field spatial image of the VCSEL emission. The spectrally-resolved far-field images are shown in Fig. 6 along with a scaled overlay of the RCPD active area. Light hitting inside of the small white ring falls on the VCSEL and that outside of the larger white ring falls on the substrate, neither of which will be collected by the RCPD. When the piezo voltage is adjusted to maximize the reflected RCPD signal, more power is in the LP11 mode which falls on the RCPD while the LP01 mode falls mainly on the VCSEL mesa.[3] Thus, as the power shifts between modes as a result of feedback from the mirror, the RCPD current can change dramatically while the total VCSEL output power shows little variation.

We have also investigated 3µm and 7µm oxide aperture devices with mirror to device separations ranging from 250µm to 1mm. In all cases, the results were consistent with those for the 5µm VCSELs detailed here. Thus, to minimize the RCPD signal variations as the VCSEL power moves between modes, the RCPD must be large enough to collect all of the VCSEL modes at the system working distance and the VCSEL shadow in the RCPD center must be minimized.

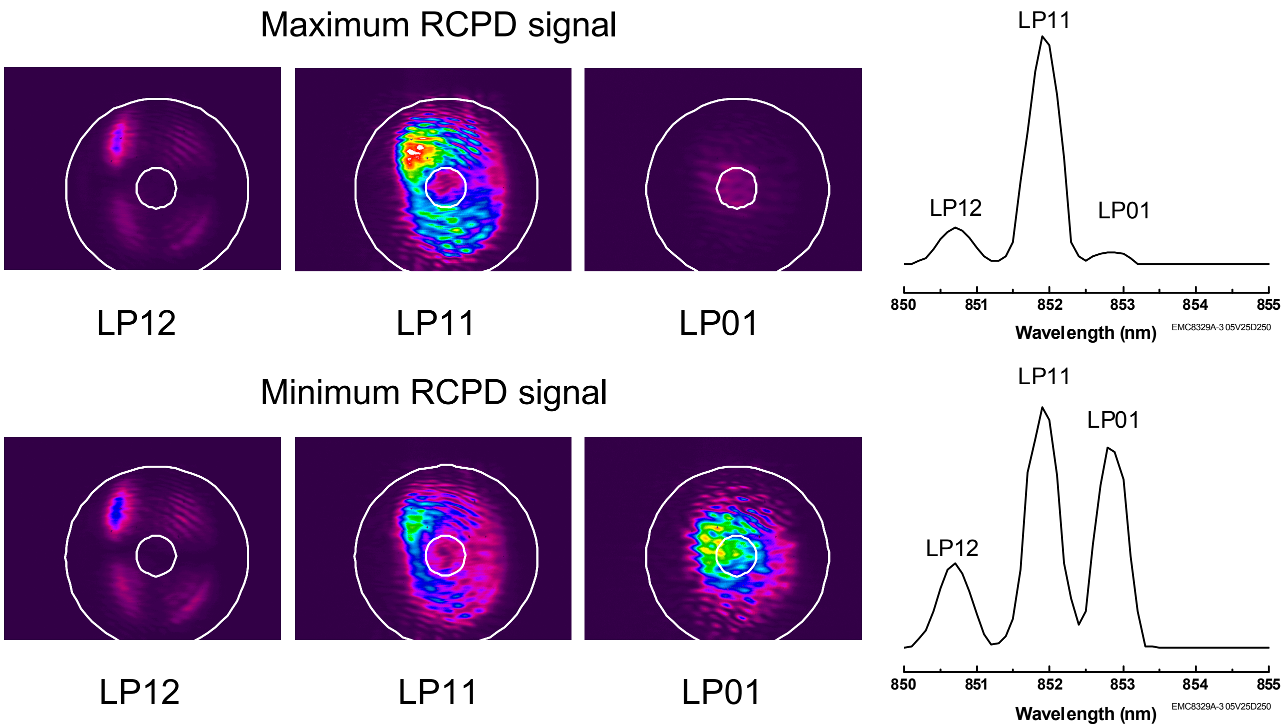
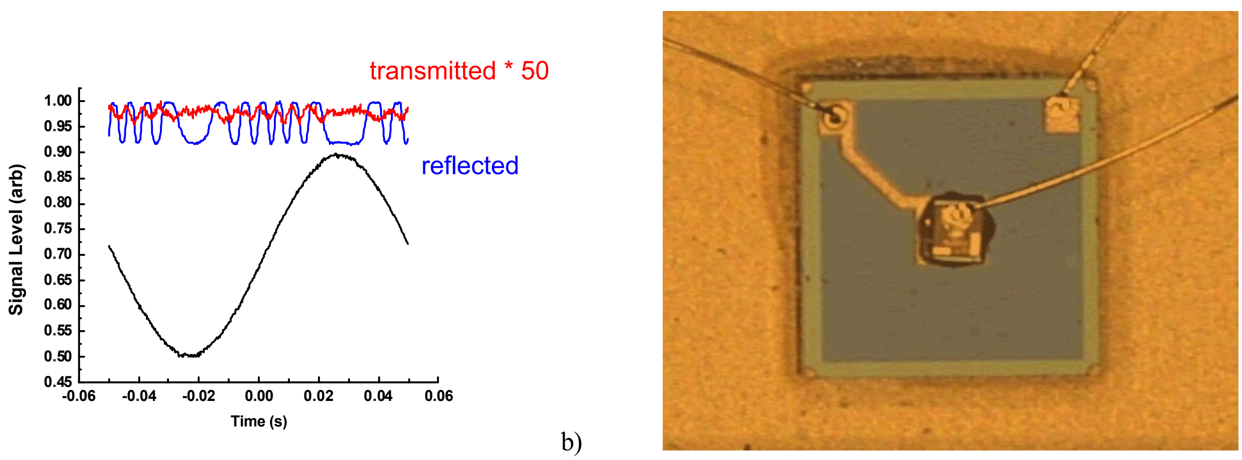


Figure 6. Far field optical modes corresponding to a maximum or minimum in the RCPD signal. The VCSEL drive current is 1.6mA with a resulting variation of ~20% in the reflected RCPD signal.

With this in mind, we mounted a 500µm square commercial multimode VCSEL die on top of a 2mm square silicon PIN photodiode as shown in Fig. 7. Here the VCSEL die shadows the fundamental mode while the higher order transverse modes are absorbed by the photodiode. Thus, as the VCSEL power moves between modes the reflected photocurrent signal varies much more than the transmitted power. The device to mirror separation was 1.6 mm at a VCSEL drive current of 3.6mA (threshold = 1.4mA).



a) b)

Figure 7. a) Feedback induced variations in the signals from a commercial 500µm square VCSEL die attached to the top of a 2mm square silicon photodiode. The transmitted signal variation is amplified by **50x** to make it visible on the plot. b) A photomicrograph of the device under test.

4. CONCLUSIONS

When using coaxial VCSEL/detector pairs as a reflective position sensor, careful consideration to the effects of feedback is warranted. Small vibrational or thermal movements of less than one wavelength can result in large variations in the photocurrent signal with no intentional change in mirror location. Indeed, with an unfortunate choice of VCSEL size, VCSEL drive current, detector size and device-to-mirror separation, more than 20% variation in the reflected signal due to optical feedback effects can be observed. These variations in reflected signal are due to power fluctuations between the different transverse modes in the VCSEL and how the modes interact with the annular detector.

When designing the coaxial devices, careful consideration of the system geometry is required including both the mirror to device separation and the larger spatial extent of the higher order modes.[4] The detector outside diameter must be large enough to collect all of the VCSEL transverse modes to minimize the detector signal variation with feedback. The size of the dark area in the center of the detector due to the VCSEL must be minimized as well. The closer the device is to the mirror, the larger the effect of the central dark area on the detector response in addition to the increased feedback into the VCSEL which will increase the variation in VCSEL output.

Another possible strategy is to use a single mode VCSEL. This will avoid movement of power into the higher order modes but will severely limit the optical power available for the sensor. In fact, the feedback into the VCSEL seems to enhance the onset of higher order transverse modes. The size of the central dark area will significantly affect the RCPD signal level since the peak of the fundamental mode will not be collected by the detector.

A less obvious choice is to use a lower quality mirror. We have found that a reflective ground spot on a black anodized metal gear provides a sufficient contrast ratio to make a useful optical monitor. The relatively rough, low reflectivity ground spot tends to homogenize the reflected mode variations on the detector while minimizing the amount of light actually fed back into the VCSEL. The required VCSEL power is higher and most of the light is wasted but good functionality is obtained.

ACKNOWLEDGEMENT

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

REFERENCES

[1] Choquette, K.D., Lear, K.L., Schneider, R.P., Jr., Geib, K.M., Figiel, J.J. and Hull, R., “Fabrication and performance of selectively oxidized vertical-cavity lasers,” Photon. Tech. Lett. **7**, 1237-1239 (1995).

[2] Serkland, D.K., Geib, K.M., Allerman, A.A. and Hargett, T.W., “Monolithic integration of vertical-cavity surface-emitting lasers and wavelength-shifted resonant-cavity photodetectors,” Lasers and Electro-Optics Society 2001, **2**, 566-567 (2001).

[3] D. Gloge, "Weakly Guiding Fibers," Appl. Opt. **10**, 2252-2258 (1971).

[4] Tai, K., Lai, Y., Huang, K.F., Huang, T.C., Lee, T.D. and Wu C.C., “Transverse mode emission characteristics of gain-guided surface emitting lasers,” Appl. Phys. Lett. **63**, 2624 (1993).