

# Continuous Tunable 1550-nm High Contrast Grating VCSEL

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**Abstract:** We report monolithic, tunable 1550-nm HCG-VCSELS with 26.3 nm continuous tuning. Room temperature CW power of >3.3 mW, and 10 Gb/s direct modulation over 100 km of fiber is demonstrated.

**OCIS codes:** (140.7260) Vertical cavity surface emitting lasers; (140.3600) Tunable lasers; (060.4080) Modulation

## 1. Introduction

Tunable lasers are important for wavelength-division-multiplexed (WDM) systems with applications including sparing, hot backup, and fixed wavelength laser replacement for inventory reduction. They give network designers another degree of flexibility to drive down overall system cost. Tunable 1550-nm VCSELS are desirable because of their simple, continuous tuning characteristics, making them promising for low cost manufacturing and low power consumption. Although several structures have been reported with wide, continuous tuning [1], [2], largely due to their fabrication complexity, low-cost tunable 1550-nm VCSELS have not yet been available on the market.

Here, we report a novel monolithic, tunable 1550-nm VCSEL structure using a high contrast grating (HCG) as the tunable mirror and proton implant to provide current confinement, leading to a wafer-scale, low cost fabrication process. A wide continuous tuning range of up to 26.3 nm was achieved. We report single-mode CW operation up to 85 °C and >3 mW CW output power at room temperature. We demonstrate >7.5 GHz 3-dB direct modulation bandwidths, and we show 10 Gb/s direct modulation through a fiber link of 80 km single mode fiber (SMF) and 20 km dispersion compensating fiber (DCF).

## 2. VCSEL Design and Performance

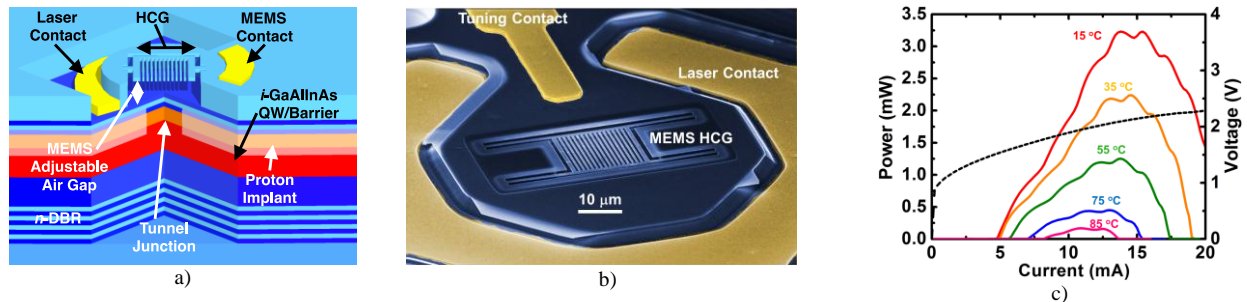


Fig. 1 (a) Schematic of a 1550 nm tunable VCSEL utilizing a suspended HCG as a top mirror which can be electrostatically actuated. (b) An SEM image of a high contrast grating integrated on the VCSEL (c) CW LIV at various heat sink temperatures ranging from 15 °C to 85 °C.

An HCG is a single, ultra-thin grating made of high index material with a subwavelength period. It has been shown to exhibit extraordinary properties such as a much broader reflection band than conventional distributed Bragg reflectors (DBR) [3]. HCGs have been implemented on VCSELS, allowing VCSELS to be fabricated with less stringent epitaxy requirements, intrinsic polarization stability and a large fabrication tolerance [3]. Tunable 850-nm VCSELS and fixed 1550-nm VCSEL have been demonstrated [4], [5].

Here, we report the first continuous, tunable 1550-nm HCG-VCSEL with a single, monolithic epitaxy and planar fabrication. Fig. 1 a) shows a schematic of the tunable VCSEL structure and the detailed design is described in previous publication [5]. The HCG is part of an electrostatically-actuated MEMS structure, which can electrostatically actuate the HCG towards the substrate, changing the lasing wavelength. Fig. 1 b) shows an SEM image of the HCG-VCSEL. Given the structure requires one single epitaxy and the critical steps are done on a planar wafer, the fabrication process facilitates low-cost, scalable manufacturing.

The VCSELS have excellent performance characteristics. Fig. 1 c) shows the temperature dependent light-current-voltage characteristic of a VCSEL with CW operation achieved up to 85 °C, and >3.3 mW CW output power at 15 °C. The ripple of the LI curve is due to residue reflection from the back of the substrate/metal interface, which can be easily eliminated by increasing bottom DBR reflection. The devices have slope efficiencies of ~0.25 mW/mA and threshold currents of 2-3 mA.

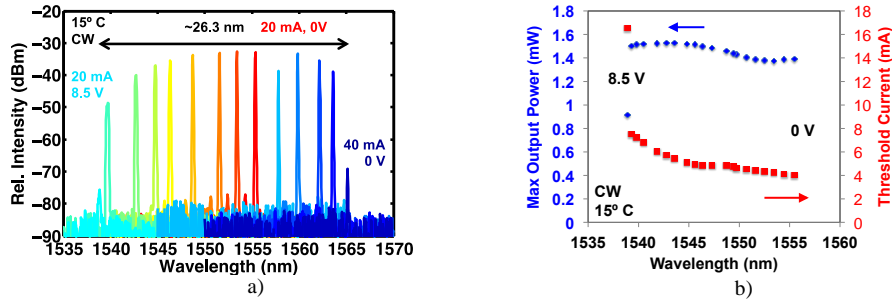


Fig. 2 a) Tuning range of a tunable HCG VCSEL. The laser lases over a range of 26.3 nm. b) The maximum output power (blue) and threshold current (red) as a function of the wavelength at 20 mA. The device outputs over 1.4 mW over most of the mechanical tuning range.

Tunable VCSELs were realized with a wide, continuous tuning range of 26.5 nm, shown in Fig. 2 a), using a combination of MEMS tuning and thermal tuning. The emission wavelength continuously blue shifts with increasing MEMS voltage. Up to 16.5 nm of continuous tuning was achieved with 8.5 V applied to the MEMS, while keeping the bias current fixed at 20 mA. Another 9.8 nm of tuning range was achieved by increasing the bias current, caused by thermal effects. Fig. 2 b) shows the maximum output power (blue) and threshold current (red) as a function of wavelength when the device is biased at 20 mA and mechanically tuned from 0 to 8.5 V. The CW optical power is  $\sim 1.5$  mW, and the threshold current is under 5 mA over almost the entire mechanical tuning range. The tuning range can be improved with further optimization of the initial mirror position relative to the structure.

### 3. Modulation and Transmission Characteristics

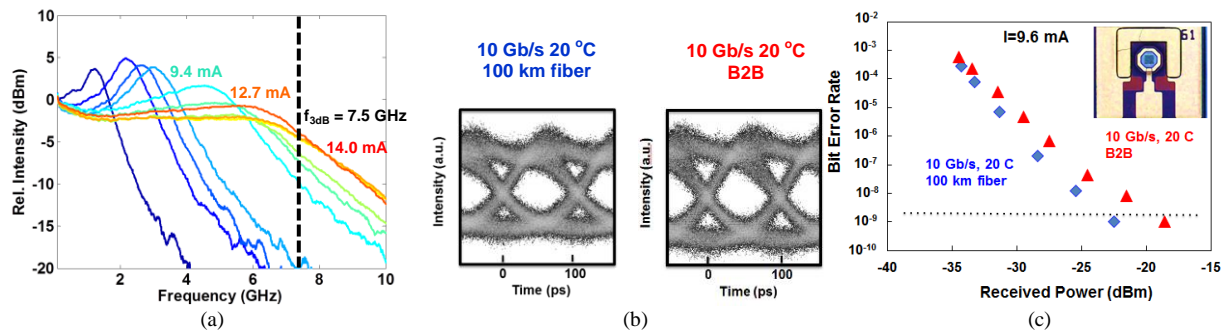


Fig. 3 a) Direct modulation (S21) of a 1550-nm HCG VCSEL under room temperature CW operation, biased at various current levels. b) Eye diagrams and c) BERs for transmission of 10-Gb/s OOK directly modulated VCSEL: back-to-back (B2B) and after transmission through 100 km optical fiber link.

The HCG-VCSEL was tested under direct modulation. S21 characteristics of a fixed wavelength VCSEL are shown in Fig. 3 a) as a function of bias. The device has a -3 dB point of 7.5 GHz, and it is currently limited by RC parasitics.

Fig. 3 b) and c) shows eye diagrams and BER curves of a directly modulated HCG-VCSEL. The device has error free ( $BER < 10^{-9}$ ) operation up to 10 Gb/s at 20 °C. Fiber transmission performance of the signal was assessed using bit-error-rate (BER) measurements before (back-to-back) and after transmission through a link consisting of 80-km SMF followed by 20 km of  $\sim -1378$  ps/nm DCF (Lucent DK-80). The BER after fiber transmission is slightly better than back-to-back which could be result from the interactions of residual chromatic dispersion and chirp.

### 5. Summary

Tunable 1550 nm HCG-VCSELs with a continuous tuning range up to 26.3 nm under room temperature CW operation is reported for the first time. Single mode CW power up to 3 mW at room temperature and operation up to 85 °C are demonstrated. Direct modulation with a  $>7.5$  GHz bandwidth was demonstrated. 10 Gb/s direct modulation was also realized with error free transmission over a 100 km fiber link. Tunable HCG-VCSELs offer a versatile, low cost, energy efficient solution for high speed networks in data center and fiber-to-the home applications.

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