

# Ultra-High-Bandwidth (>35 GHz) Electrooptically-Modulated VCSEL

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**Abstract:** Electrical bandwidth of 60 GHz and optical bandwidth exceeding 35 GHz, limited by the photodetector response, are demonstrated for an electrooptically-modulated VCSEL. The maximum single mode power approaches 3mW continuous wave. Modulation voltage efficiency factor is 3-10 dB/V.

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**OCIS codes:** (250.7260) Vertical cavity surface emitting lasers, (060.4080) Modulation (060.2360).

## 1. Introduction

There exists a growing interest in ultrahigh bandwidth low cost signal transmission through multimode fiber [1, 2]. Recently, multimode fiber was shown to be capable to 40 Gb/s transmission over 600 m [3] with good coupling tolerances. Thus, there is a need for low cost, high-speed emitters and vertical cavity surface-emitting lasers (VCSELs) are predestinated to play that role.

## 2. Concept and fabrication of the EOM/VCSEL

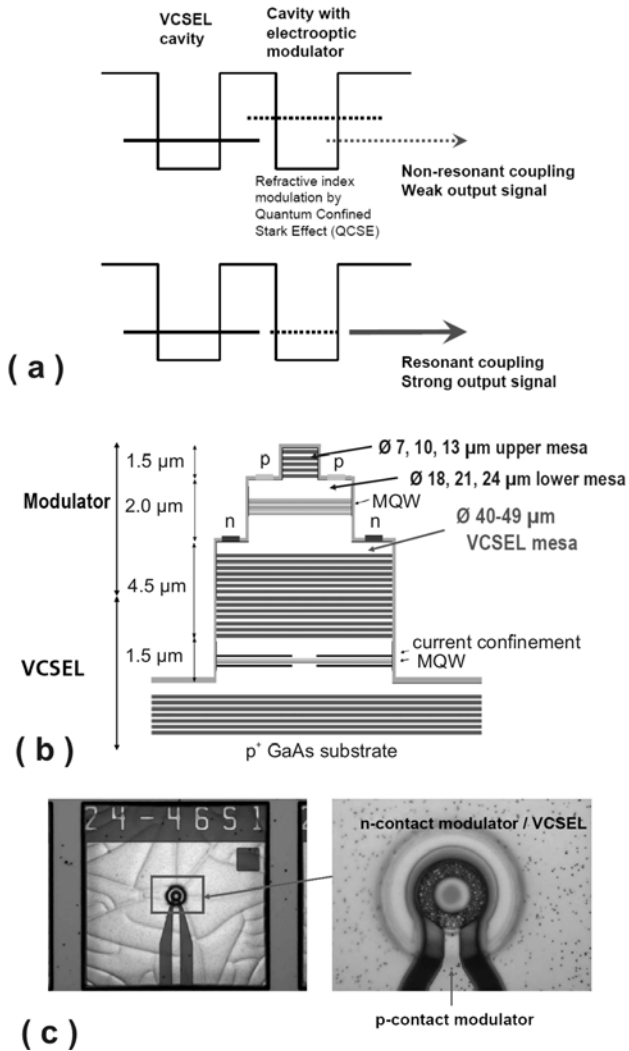
The device addressed is based on resonant interaction between two or several cavities and can be realized in surface-emitting geometry or also as a tilted cavity edge-emitter. The device contains at least one wavelength-tunable element controlled by an applied voltage and at least two resonant cavities. The resonant wavelength of the tunable element is electrooptically modulated (EOM) using the quantum confined Stark effect with respect to the resonant wavelength of the other cavity, resulting in a modulated transmittance of the system (Fig. 1a). The device contains at least three electric contacts to apply laser drive current and reverse modulator bias, as schematically shown in Fig. 1b.

The EOM/VCSEL heterostructure was grown by a molecular beam epitaxy (MBE) using a RIBER MBE49NT machine on a GaAs(100) p-doped substrate. P-doped and n-doped distributed Bragg-reflectors were composed of  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  and GaAs layers. The VCSEL and the modulator cavity were modeled to operate at ~960 nm with a blue shift of the modulator cavity by ~ 3-4 nm. The detuning of the cavities was controlled by optical reflectance and photo-reflectance spectroscopy and varied across the wafer. Strain-compensated multiple quantum wells (MQWs) were used to provide VCSEL gain at ~960 nm. Strain-compensated MQWs with a strong absorption peak at ~930 nm were introduced in the modulator section. The Q-factor of the modulator section was chosen to be low enough to avoid noticeable absorption in the modulator cavity, minimize chirp in the VCSEL cavity, and ensure efficient light outcoupling.

The sizes of the modulator and VCSEL mesas were chosen to be compatible with > 40 Gb/s modulation frequency. BCB planarization was applied for low capacitance contact pads. Wet thermal oxidation of the VCSEL aperture was performed at 400°C. Optical microscope images of the device are shown in Fig. 1c.

## 3. Electrical properties

In order to better assess the high speed potential of such devices,  $S_{11}$  impedance measurements were performed under different bias voltages. A remarkably good uniformity in the characteristics of devices having similar geometry was manifested. The estimated electrical modulation bandwidth was increasing with decreasing of the modulator mesa size from ~33 GHz for 24  $\mu\text{m}$ -mesas to ~59 GHz for 18  $\mu\text{m}$ -mesas, scaling with their surface area

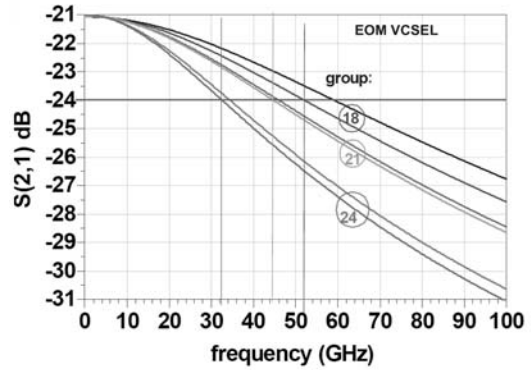


**Fig. 1.** Basic idea of the EOM/VCSEL device (a). The coupling between the active and the modulator cavity can be tuned using the EOM effect in the modulator cavity. For resonant conditions (bottom) the transparency of the system to light increases. Schematic geometry (b), optical microscope image (c) of the EOM/VCSEL device.

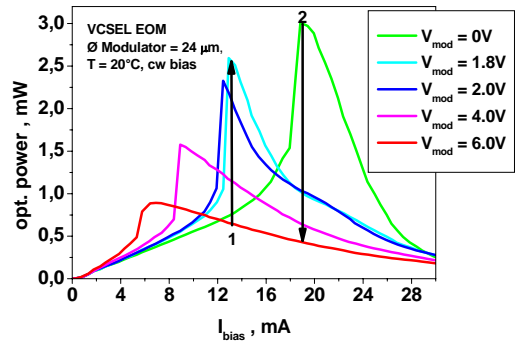
emission spectrum with an OSA. Device characteristics proved to strongly depend on the layer structure, respectively, the detuning of the two resonant cavities.

*Small detuning:* Fig. 3 shows a typical static modulation performance of an EOM/VCSEL device in the case of small detuning between the VCSEL and the modulator cavity. At zero bias the light-current (L-I) dependence shows a strong resonant feature. This effect originates from thermal shifting of the QW exciton absorption peak in the modulator section, and the related tuning of the modulator cavity. When the reverse bias is applied to the modulator section, there is an additional contribution of the refractive index modulation due to the EOM effect, which shifts the resonance feature towards smaller currents. We were, thus, able to demonstrate 2.6d B/V intensity modulation at very small bias voltages.

*Large detuning:* The devices fabricated from a different part of the wafer with a larger detuning between the cavities required higher reverse bias voltages to reach the resonance transparency condition (s. Fig. 4). The spectral behavior of a single-mode device is shown Fig. 5 and evidences wavelength chirp on a level  $\sim 0.3$  nm/V. We believe that the operation voltage can be adjusted by reducing the thickness of the modulator section. No significant change in the threshold current was observed. A two-fold increase of the differential efficiency near threshold indicated a significant increase in the external losses and, respectively, the low absorption losses in the modulator section



**Fig. 2.** Electrical bandwidth of the devices having different modulator mesa sizes (in circles). The speed scales with the surface of the modulator mesa, which defines the capacitance.



**Fig. 3.** Static performance of an EOM/VCSEL at different reverse biases applied to the modulator section (small detuning between the cavities).

(see Fig. 2). This demonstrates the big high-speed potential of these devices and confirms the compatibility of the fabrication technology with  $> 40$  Gb/s modulation regime.

#### 4. Optical properties: Static performance

Optical properties (cw) of on-wafer devices were evaluated by L-I curves at different modulation bias voltages, as well the observation of the

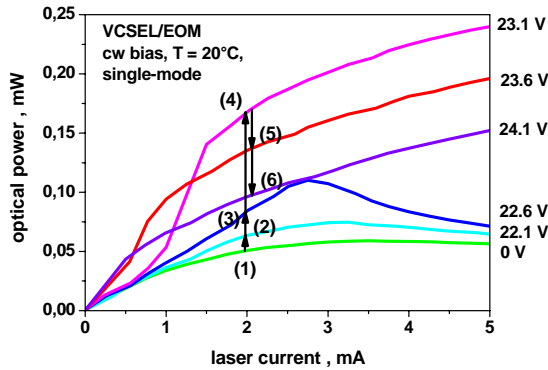


Fig. 4. Static performance of the EOM/VCSEL at different reverse biases applied to the modulator section (large detuning between the cavities).

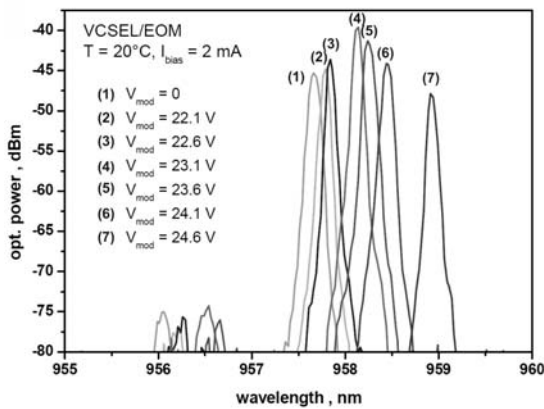


Fig.5. Spectra of a single-mode EOM/VCSEL device at different reverse biases applied to the modulator section (large detuning between the cavities). At the resonant conditions, an intensity modulation of 5 dB/V is observed.

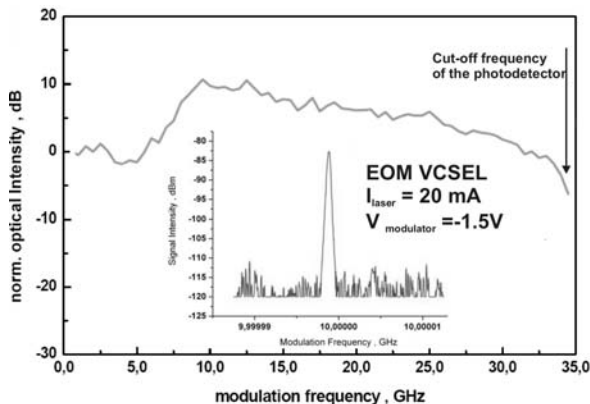


Fig.6. Optical modulation performance of the EOM/VCSEL. The maximum bandwidth is system limited. Insert shows the modulation response of the optical signal at 10 GHz. A ~35 dB suppression of parasitic frequencies and a quasi-ideal ( $<10^{-7}$ ,  $<1$  kHz) width of the optical response signal is observed

Equivalent VCSEL devices showed high temperature stability, demonstrating cw operation at  $T > 80^{\circ}\text{C}$ .

**5. Optical properties: Dynamic performance**

The optical modulation performance of these devices was studied in the 0 – 40 GHz frequency range. For this on-wafer test, the electrical modulation signal was coupled to the device through a high-frequency contact head. As shown in Fig. 6, the modulation bandwidth exceeded 35 GHz (see Fig. 6) and was limited by the cut-off frequency of the photodetector.

**6. Conclusion**

In conclusion, we were able, to our knowledge for the first time, to demonstrate EOM/VCSEL devices with a resonant cavity design and non-

absorbing modulator part. This novel design provides several important advantages such as:

- Monolithic vertically-integrated device in low-cost VCSEL geometry
- Ultra-low capacitance enabling bandwidths exceeding  $> 60$  GHz,
- The modulator driver is a low-current device with a small heat dissipation and lower cost
- The speed of the device is not defined by the power density in the VCSEL cavity.
- Combination of wavelength tuning and intensity modulation by adding several modulator sections is possible.
- Built-in photocurrent control for failure detection and extended functionality

These devices can be implemented into ultrahigh-speed signal transmission systems and, in combination with special novel multi-mode fibers [3], significantly reduce installation and maintenance costs in local area networks, in radio over fiber distribution systems and in computer backplanes.

**7. References**

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