Air-Cavity Dominated HCG-VCSEL with a Wide Continuous Tuning

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Abstract: We present continuously tuned emission of 940-1000 nm wavelength from an electrically-pumped VCSEL without top DBR layers via an electrostatically controlled HCG mirror. Large tuning range results from a high optical intensity in the air cavity.

OCIS codes: (140.7260) Vertical cavity surface emitting lasers; (140.5960) Semiconductor lasers

1. Introduction

Widely tunable lasers are highly desired for application such as optical coherence tomography (OCT), light detection and ranging (LIDAR) and dense wavelength division multiplexing (DWDM) application. Because of their compact design and low cost, wavelength tunable micro-electro-mechanical structure (MEMS) vertical cavity surface emitting lasers (VCSELs) are extremely promising for the mentioned application space.

In this paper, we present a new HCG tunable VCSEL design where we completely removed all distributed Bragg reflector (DBR) layers from the top mirror. The VCSEL top reflection is solely provided by a high contrast grating, which is freely suspended by a MEMS structure above the epitaxy layers via an air gap, forming an air cavity above the semiconductor cavity centered at the active layers. Recently, we reported VCSELs with a MEMS actuated high contrast grating (HCG) top mirror and 73 nm tuning range at 1060 nm [1]. In that paper, we discussed an interesting coupling mechanism formed between these two cavities, i.e. semiconductor and air cavity. The strong coupling led to a record tuning ratio of a VCSEL [1]. In this paper, we further removed the excess top DBR layers in [1] to reduce VCSEL drive voltage and resistance. We present experiment results with a wide 56 nm tuning range centered at 967 nm. This is the first demonstration that a VCSEL can lase entirely with the reflection of HCG and without any top DBRs. The lasing wavelength and the non-lasing Fabry Perot (FP) modes are measured as a function of tuning voltage and hence the air gap size. Excellent agreements are obtained between simulation and experimental data, showing a clear signature of the novel air-dominated cavity.

2. Device Structure

The presented HCG VCSEL was grown in-house by Metal-Organic Chemical Vapor Deposition (MOCVD) on a substrate of 33 pairs of distributed Bragg reflector from Landmark Optoelectronics Corp. TBA and TBP were used as group-V precursors. After desorption of the protective GaAsP layer terminating the DBR substrate [2], a GaAs buffer was grown. The active region is composed out of 5 InGaAs/GaAsP strain compensated quantum wells, surrounded by AlGaAs cladding. Then the oxidizable $Al_{98}GaAs$ layer and a p-GaAs layer as laser top contact were grown. After this a 25nm thick InGaP layer serves as etch stop and is followed by 1.134 μm thick GaAs, to be selectively removed by wet etching to define the air cavity. The 278 nm thick n-$Al_{60}GaAs$ HCG layer terminates the air cavity. A final n-GaAs cap layer serves as protection during fabrication. Being able to grow the described structure separately from the bottom DBR, reduced the total thickness of the grown structure to less than 2.5 μm, which resulted in a growth time of less than 2.5 hours. Additionally, the presented design eliminates any top DBR pairs, resulting in an increased free spectral range of 59 nm and simplifies the theoretical description of the device (micrograph shown in Fig. 1 (a)).

3. Electrostatic Tuning

After fabrication, the electrostatic tuning range was tested. Under application of a static reverse bias between n-doped HCG layer and the p-doped laser contact, the wavelength was tuned continuously for 56 nm from 1001 nm (at 0 V) to 945 nm wavelength (at 15.7 V). While maintaining >25dB side mode suppression ratio (Fig.1 (b)), almost the entire free spectral range of 59 nm was covered by static tuning. Fig. 1 (c) shows an exemplary LIV characteristic near the center of the tuning range at 968nm. Here we observed a low threshold of 1mA and peak power of close to 0.7 mW.

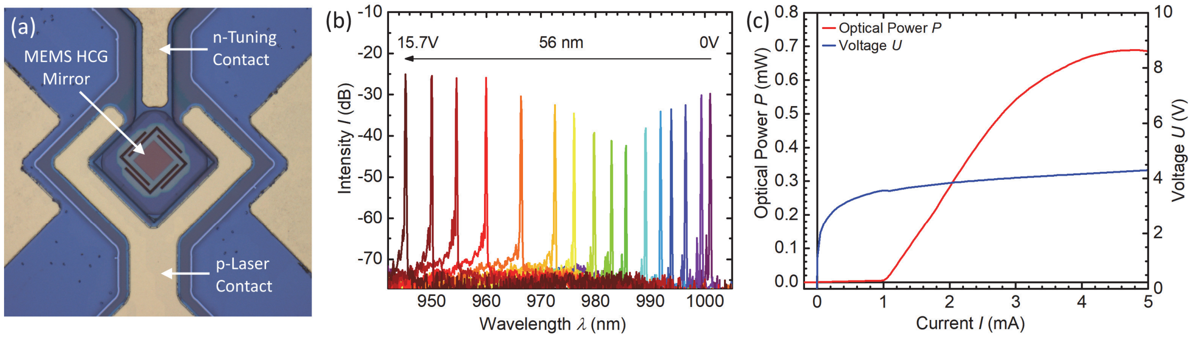

Fig. 1 Wavelength tunable laser: (a) Micrograph of an device; (b) Electroluminescence spectra showing 56 nm electrostatic tuning range; (c) Exemplary LIV curve neer the center of the tuning range at 968nm and 14V tuning voltage.

In the following, the measured wavelength-tuning characteristic shall be compared to the simulated dependence of lasing wavelength on the air gap size. First, the emission wavelengths of the lasing mode (and non-lasing longitudinal modes) are obtained from the emission spectra at different tuning voltages. To relate the measured tuning voltages to the corresponding air cavity length the resonance frequency of the MEMS HCG mirror was determined, from the dependence of the dynamical tuning range as function of tuning frequency. The normalized change in wavelength range with AC tuning frequency is shown in Fig. 2 (a). A resonance frequency of 345 kHz and -3 dB frequency of 687 kHz were measured. Next, the spring constant k was calculated assuming a harmonic oscillator and resonance frequency $\omega = \sqrt{k/m}$, with the mass of the HCG mirror based on geometry. Fig. 2 (b) shows the length of the air cavity at static equilibrium as a function of tuning voltage. At 0 V the length of the air cavity equates to the thickness of 1134 nm of the sacrificial GaAs layer The calculated pull-in voltage of 16 V fits very well to the experimentally observed range of pull-in voltages.

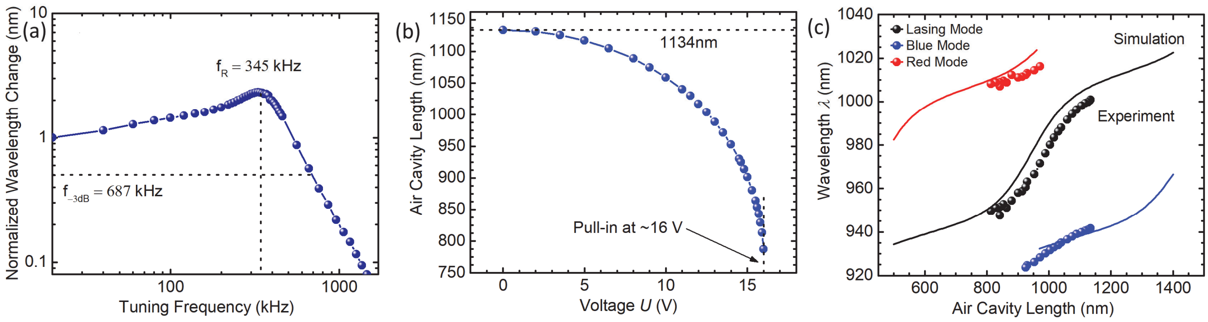

Fig. 2 Comparison of measured wavelength-tuning characteristic simulation (a) Measurement of the mechanical resonance of the MEMS HCG mirror; (b) Calculation of air cavity size as function of tuning voltage; (c) Experimental (dots) and simulated results (lines) for the wavelength of longitudinal modes of the air cavity. The fast change of lasing wavelength vs. air gap length is a clear signature of ACD design.

Finally, the emission wavelengths of the experimentally observed modes are plotted as function of the air cavity length in Fig. 2 (c). The experimental results (dots) are in very good agreement with the transfer matrix simulation (lines). The simulation parameters are within resolution of the SEM measurements of HCG period and epitaxial layer thicknesses. The stronger dependence of wavelength on the change in length of the air cavity (both in simulation and experiment), indicates the successful realization of an air-cavity dominant (ACD) design, which optimizes the free spectral range, and therefore the maximum tuning range of the device [1]. A further increase in free spectral range can be achieved by eliminating the more than 600 nm thick n-contact layer below the active region in parts or in total, which would increase the simulated tuning ratio to 7.1%. Further, by substituting the graded interface DBR by an abrupt interface AlAs/GaAs DBR to reduce the effective cavity length, we expect to increase the tuning ratio close to 9%.

4. References

[1] P. Qiao et al., "Wavelength-Swept VCSELs" JSTQE **23**, 6 (2017)
[2] J. Wang et al., "Precise Two-step Growth of 940-nm VCSEL on a GaAsP-capped DBR Wafer" CLEO, (2018), *Submitted*