Thermal wavelength stability of ultraviolet-B vertical-cavity surface-emitting lasers enabled by short cavity length and dielectric mirrors

L. Persson*[1], J. Ciers[1], F. Hjort[1], and Å. Haglund[1]
Department of Microtechnology and Nanoscience
Chalmers University of Technology
Gothenburg, Sweden
*E-mail: lars.persson@chalmers.se

***Abstract*— For wavelength-sensitive applications, the lasing wavelength shift with temperature should be negligible. In vertical-cavity surface-emitting lasers (VCSELs), this wavelength shift is set by the resonance shift with temperature. We here propose and demonstrate an approach to drastically reduce this temperature dependence by compensating the inherent redshift by the semiconductor cavity with a blueshift induced by the dielectric distributed Bragg reflectors (DBRs) in short-cavity lasers. This was implemented in optically pumped VCSELs emitting at 310 nm, which resulted in lasers with a measured blueshift of less than 0.1 nm over 80°C with a maximum slope of 3.4 pm/K, to be compared with the redshift of about 1-1.5 nm over the same temperature range reported for III-nitride blue-emitting VCSELs. This concept to achieve a more temperature-stable lasing wavelength is generic and could be applied to any VCSELs.**

Keywords—VCSEL; UV; temperature stable.

I. INTRODUCTION

Wavelength-sensitive applications, such as gas sensing and atomic clocks, require lasers with a stable emission wavelength. In such applications, vertical-cavity surface-emitting lasers (VCSELs) are often preferred since the lasing wavelength shift with temperature is set by that of the resonance rather than that of the gain peak, and the lasing wavelength therefore shifts less with temperature. III-nitride VCSELs have shown a redshifting lasing wavelength with increasing temperature in the range of 12-18.5 pm/K [1], caused by the increasing refractive index n, with temperature T, of the semiconductor materials used in the cavity. Dielectric materials on the other hand can have a negative dn/dT [2,3]. We here present a way of compensating the inherent redshift in the laser by including dielectric materials featuring negative dn/dT in the DBR. This is implemented in a short cavity VCSEL to maximize the influence of the dielectric materials and we thereby achieve a temperature stable emission wavelength of an AlGaN-based UVB-emitting VCSEL.

II. RESULTS

We recently demonstrated optically pumped UVB VCSELs emitting around 310 nm [4]. Fig. 1 shows a schematic view of such a laser that consists of a 2.5λ $Al_{0.6}Ga_{0.4}N$ cavity with 3 AlGaN QWs surrounded by two dielectric HfO_2/SiO_2 DBRs, realized by a substrate removal technique using electrochemical etching [5]. The optical spectra as a function of heat-sink temperature T_{hs} is shown in Fig. 2. A blueshift of less than 3.4 pm/K is seen over a temperature range of 80°C. We attribute this wavelength stable behavior to compensating effects in dn/dT between the AlGaN cavity and the dielectric DBRs. The refractive index as a function of temperature for the different materials was experimentally determined, see Fig. 3. To calculate dn/dT for AlGaN, Brunner's model [6], together with measured values of the band edge shift with temperature of $Al_{0.6}Ga_{0.4}N$, was used. For the dielectric materials, sputtered SiO_2 and HfO_2 films were deposited on Si, placed on a heated stage and measured by ellipsometry. The $Al_{0.6}Ga_{0.4}N$ has a positive dn/dT while it is negative for the dielectric materials, leading to the claimed compensating effect. Effective index simulations including these measured temperature dependencies for the refractive index reproduce the temperature-stable behavior, as seen in Fig. 4. Without a negative dn/dT in the dielectric layers, the resonance wavelength redshifts linearly with temperature as typically seen in VCSELs. Fig. 5 indicates that short cavities (about 2.5λ) are required to achieve a temperature stable emission wavelength. This is because for shorter cavities, the penetration depth of the optical field into the DBRs is significant in relation to the overall cavity length. This leads to an efficient compensation of the increasing round-trip phase shift with temperature of the AlGaN by the decreasing round-trip phase shift with temperature of the DBRs.

The concept proposed and demonstrated here to achieve a temperature-stable emission wavelength from a VCSEL is a generic approach and can be applied to any VCSELs as long as they allow for the use of short cavity lengths and materials with negative dn/dT.

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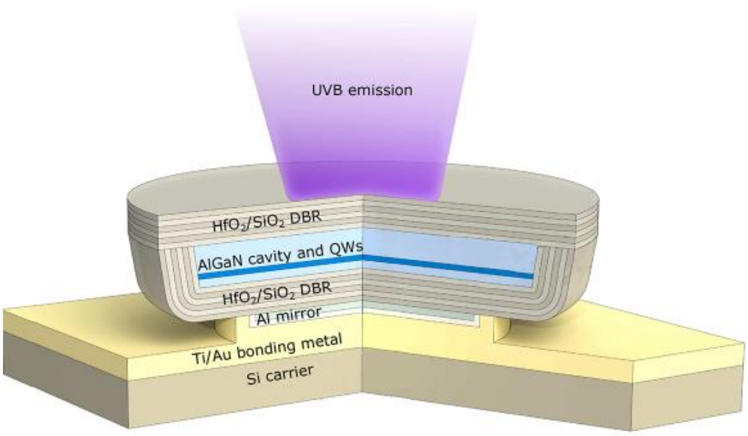

Fig. 1. Schematic view of the UVB VCSEL featuring an AlGaN cavity and dielectric DBRs.

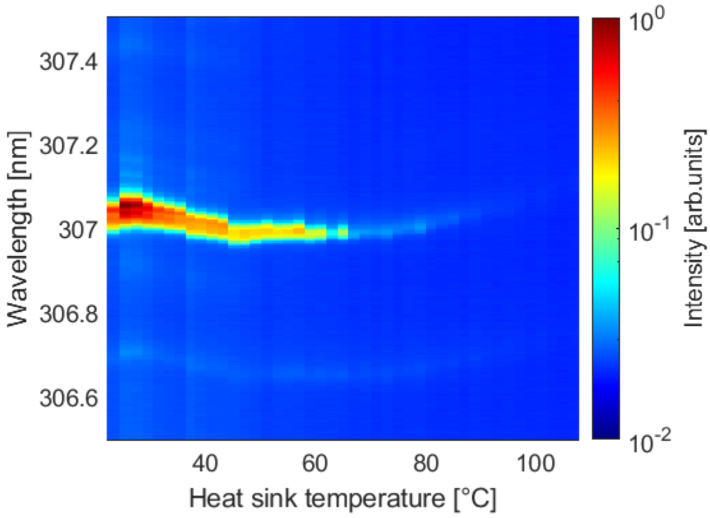

Fig. 2. Optical emission spectrum for a UVB VCSEL as a function of temperature and with intensity in logarithmic scale.

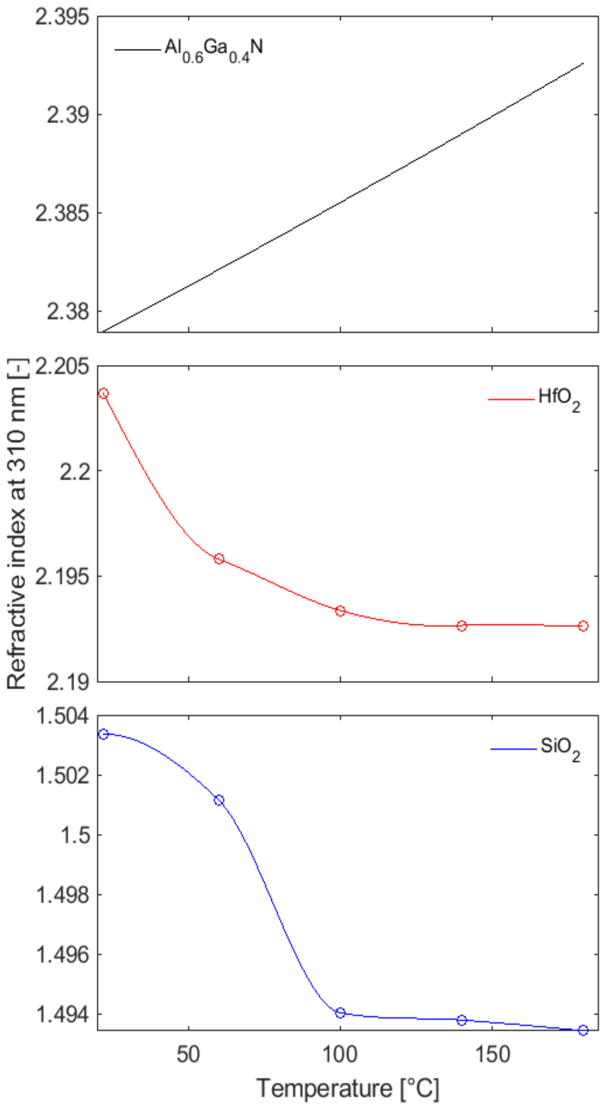

Fig. 3. Experimentally determined refractive index as a function of temperature for $Al_{0.6}Ga_{0.4}N$, HfO_2, and SiO_2.

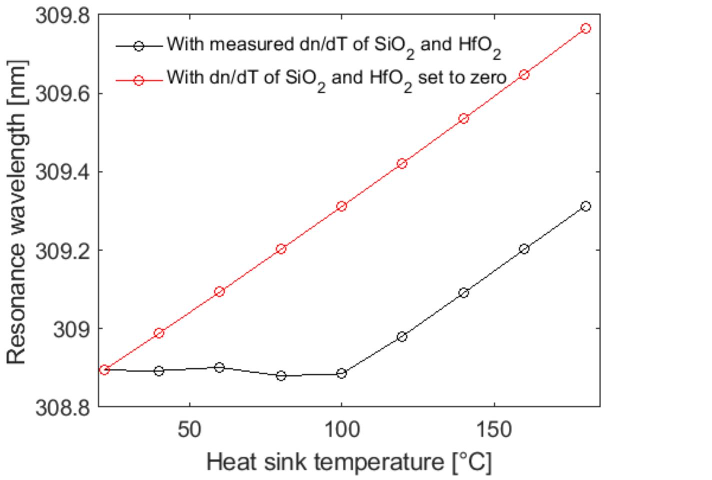

Fig. 4. Resonance wavelength as a function of heat sink temperature, including (black) and excluding (red) the impact of the dielectric thermo-optic coefficients. The resonances were calculated using the effective index simulations assuming refractive index data from Fig. 3 for a 2.5λ cavity.

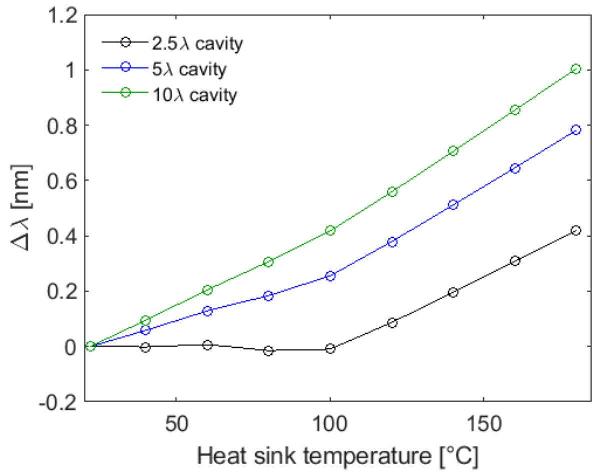

Fig. 5. Calculated resonance wavelength shift versus heat sink temperature for different cavity lengths.