VCSEL wavelength tunability using controlled mechanical strain

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Abstract

Vertical-Cavity Surface-Emitting Lasers (VCSELs) have gained prominence in data centers due to their cost-efficiency and low-power modulation. Studies showed the possibility of changing the output properties of VCSELs notably, polarization switching, polarization chaos, and even wavelength tuning by modifying the structure of the VCSEL via anisotropic strain along the crystallographic axes.

In our study, we apply controlled mechanical strain to precisely tune the wavelengths of an array of off-the-shelf 1550nm VCSEL chips using a four-point bending module. This strain induces changes in refractive indices along crystallographic axes via the elasto-optic effect, resulting in birefringence changes within our VCSELs. We investigate the relationship between mechanical strain, birefringence, and wavelength. Varying the strain level produces a consistent wavelength shift of up to 1 nm for different current values, displaying a fairly linear correlation.

Our demonstration enhances the understanding of VCSEL behavior and opens new avenues for optical communication applications.

Introduction

Vertical-Cavity Surface-Emitting Lasers (VCSELs) play a crucial role in optoelectronics, especially in data centers, thanks to their cost-efficiency and low-power modulation. Renowned for their unique structure with a vertical gain region and distributed Bragg reflectors (DBRs), VCSELs emit light perpendicular to the substrate, making them ideal for various applications, notably optical communication. The resonance condition within the VCSEL cavity, governed by the thicknesses of semiconductor layers in the DBRs, is pivotal in determining the emitted wavelength[1].

Research on VCSELs has shown that we can intentionally induce controlled modifications in their output properties. This is achieved through the intentional application of anisotropic strain along specific crystallographic axes [2]. State of the art has shown the potential of manipulating VCSEL output properties, such as polarization switching[3] and polarization chaos[4], through selective modification of the lattice constants of the semiconductor materials, through the elasto-optic effect[5] these modifications give rise to changes in the refractive indices, consequently leading to changes in birefringence within the VCSELs.

Our present study seeks to contribute to this area of research by studying the impact of controlled mechanical strain on the wavelength characteristics of VCSELs. In our study we use a four-point bending module which allows precise control over the induced strain, thereby enabling the systematic investigation of the wavelength changes of different

VCSEL chips in an attempt to establish strain induced wavelength tuning. The ability to precisely tune VCSEL wavelengths through controlled strain not only deepens the comprehension of VCSEL behavior but also introduces new prospects to their potential applications.

Experimental setup

For our experiments we use 1550nm VCSEL chips, in order to bend the VCSEL, we fix the device on top of a printed circuit board (PCB) structure as shown in figure 1-c. Printed circuit boards are made of a bendable material, in my study we are using FR4 material. The strain is applied to the VCSEL using a custom four-point bending module, the principle is shown in figure 1-a. The PCB is fixed well centered compared to the rods forming the different loading pins, the advantage of using the four-point bending technique is to ensure that the sample between the two inner loading pins is subjected to a constant bending moment, the bending moment is translated to strain and stress on the VCSELs. With this technique we are certain that the 4 VCSELs within the array are subjected to the same strain. The strain level is controlled by a micrometer screw, allowing for a comprehensive analysis of VCSEL dynamics across varying strain levels.

In order to power the VCSELs in this experiment we used probe needles directly on the connection pads of the VCSEL, suitable needles were chosen as not to damage the connections as well as to minimize any external strain that could alter experimental results.

The optical setup for our experiments employs a collimation lens with a 3mm focal length, a set of mirrors for light guidance, a linear polarizer (LP) for polarization control, an optical isolator (OI) to eliminate any potential feedback effects on our VCSEL, after the optical isolator we couple the light into a multimode fiber (MMF) used for measurement on an optical spectrum analyzer (OSA).

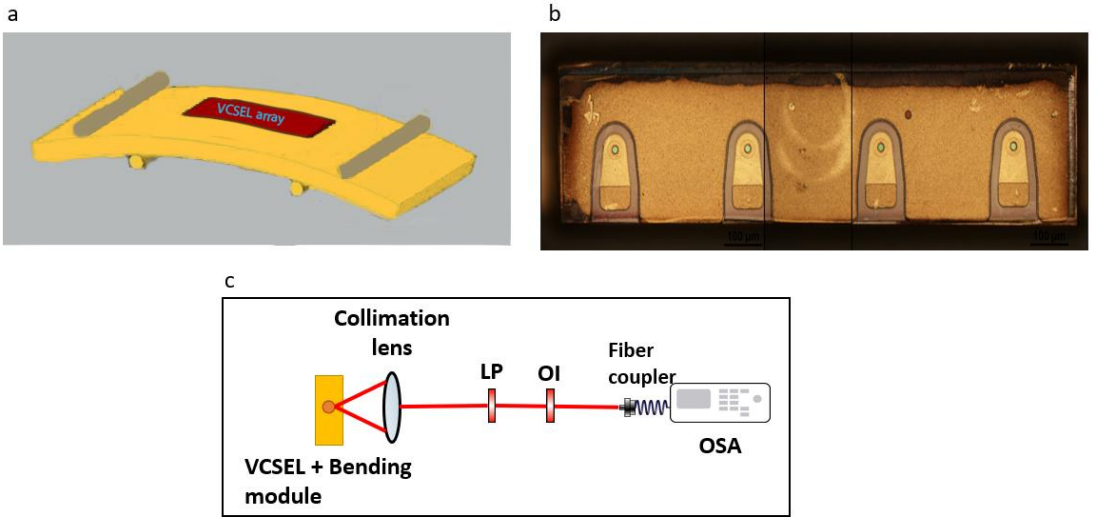

Figure 1: a) Schematic of the four-point VCSEL bending module. b) 1550nm VCSEL chips integrated on top of a FR-4 substrate from left to right VCSELs 1-4. c) scheme of the experimental setup.

Results and analysis

In our experiment we study the effect of strain on the output properties of our laser emphasizing the wavelength evolution as well as the polarization of the output light. The measurements were conducted on the whole array of VCSELs, we report the results of our measurements in figure 2, we showcase the measurement of one of the VCSELs, namely VCSEL-1 and we report that the results are similar from one VCSEL to another.

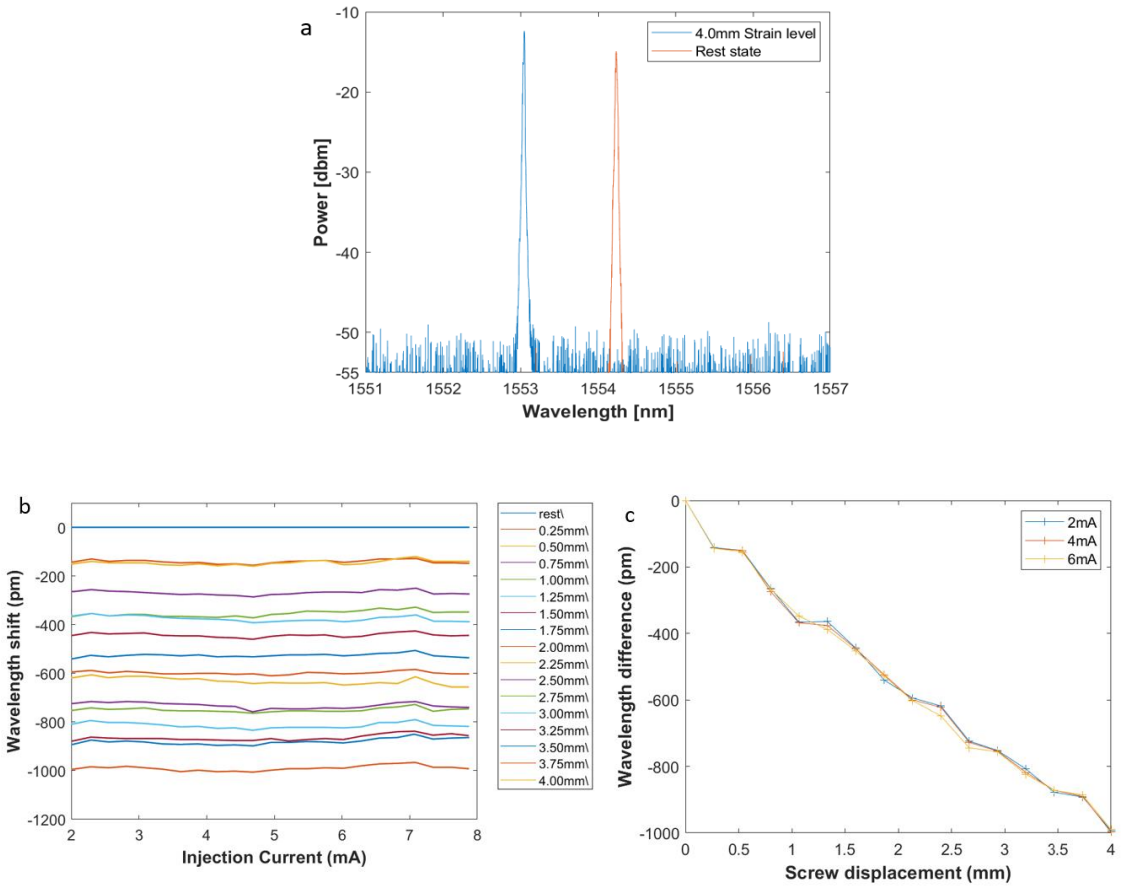

Figure 2: Experimental results a) Typical optical spectrum for injection current of 3 mA, at rest state in orange and at maximum strain measurement corresponding to a screw displacement of 4mm in blue. b)) Evolution of wavelength shift with injection current for different strain levels. c) Evolution of wavelength shift as a function of screw displacement at different injection current values.

Figure 2-a compares the optical spectrum of VCSEL-1 driven at a current of 3mA, both at the rest state and under a strain level corresponding to a screw displacement of 4mm. The observation reveals that strain induces a blue shift in the laser's wavelength, a phenomenon consistent across all quadrants of Figure 2.

To further observe and characterize this strain-induced blue shift, we normalize the wavelength shift. To achieve this, we subtract the peak wavelength of each strain level from the reference rest state (considered as 0 wavelength shift). Applying this normalization to each strain level, we obtain Figure 2-c. The evolution of this wavelength difference as a function of injection current demonstrates the independence of the effects of strain and injection current on the wavelength change. The trend appears relatively

constant. The reproducibility of this effect among the VCSELs in our experiment leads us to the conclusion that strain indeed induces a blue shift in VCSELs. Importantly, this shift remains independent of the shifts caused by thermal effects and changes in injection current, factors previously studied in depth[6].

To identify trends, we examine three different current levels and observe their evolution under various strains. The results, illustrated in Figure 2-c, pertain to VCSEL-1, exhibiting the highest recorded wavelength change. For clarity, we set the reference point at a screw displacement of 0.25mm to compensate for measurement errors at rest state. The initial point on the graph indicates a red shift of approximately 150-200 pm. Notably, at different current levels, the wavelength change demonstrates consistent behavior, revealing a linear correlation between wavelength shift and strain level as reflected by the screw displacement.

Conclusion:

In summary, our study investigated how controlled mechanical strain impacts 1550nm VCSEL chips, revealing a consistent wavelength shift of up to 1 nm across various current values and strain levels. Significantly, VCSEL 1, 2, and 3 exhibited comparable tuning rates of 302 pm/mm, 278 pm/mm, and 264 pm/mm, respectively. This exploration deepens our understanding of how VCSELs respond to strain and holds practical promise for optical communication applications. The intentional application of mechanical strain emerges as a valuable tool for precise wavelength tuning, offering potential advancements in the practical implementation of optoelectronic technologies.

References:

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