# Piezoelectric Birefringence Tuning of Vertical-Cavity Surface-Emitting Lasers

Tobias Pusch

*Exploiting the polarization dynamics of spintronic vertical-cavity surface-emitting lasers (VCSELs) can be a potential alternative to direct intensity modulation for high-speed data transmission. The frequency difference between the two fundamental linear polarization modes in VCSELs, the so-called birefringence splitting $B$, is the key parameter. For later applications, easy handling and control of $B$ is favored, which can be realized by electrical birefringence tuning. In an integrated chip, thermally induced strain via asymmetric heating with a birefringence tuning range of 45 GHz was shown. In this article we present our work on VCSEL structures mounted on piezoelectric transducers for strain generation. Furthermore we investigate a combination of both techniques, namely VCSELs with piezo-thermal birefringence tunability.*

## 1. Introduction

VCSELs are the emitters of choice for short-distance data transmission owing to their beneficial properties like low energy consumption, high fiber coupling efficiency, and low production cost [1]. Commercial devices with data rates of 25 . . . 28 Gb/s are currently being deployed. Data rates of 71 Gb/s (using transmitter equalization [2]) and 150 Gb/s (with higher-order modulation [3]) have already been shown. To reduce system complexity and increase the efficiency, a higher modulation bandwidth of the emitter is needed. An increase of the intensity modulation bandwidth is physically limited. Polarization dynamics in VCSELs are much faster and can be a promising alternative [4]. The frequency difference between the two fundamental linear polarization modes, the so-called birefringence splitting, is the determining factor for the polarization dynamics in a spin-VCSEL [4]. By inducing carrier spin in a birefringent VCSEL, an oscillation in the degree of circular polarization with an oscillation frequency close to birefringence splitting can be generated [5]. In combination with the capability to stop the oscillation after a very short time interval, this could be the basis for ultrafast dynamics in future devices [6]. Using the elasto-optic effect, the birefringence splitting in VCSELs can be manipulated. To do so, asymmetric strain has to be induced along a crystal axis parallel to one of the two preferred linear polarization directions. In 2015 we showed a record-high birefringence splitting of $B = 259$ GHz by direct bending of a VCSEL array [7]. For convenient operation and miniaturization, thermally induced splitting can be used. A first attempt to alter the strain thermally was reported by Jansen van Doorn et al. [8] using an external laser spot focused close to a VCSEL mesa. The birefringence splitting was increased irreversibly up to $B = 23$ GHz. With a keyhole-shaped VCSEL design we realized asymmetric heating close to the active area with a birefringence tuning range of $\Delta B = 45\,\text{GHz}$ [9]. In this paper we focus on strain inducing in VCSELs via a piezoelectric substrate, which combines electrical control and easy handling on a small scale.

In Sect. 2 we show the preparation steps to fabricate VCSEL arrays with extremely small sample thickness as needed to induce strain piezoelectrically. In Sect. 3 optical spectra and light–current–voltage curves for different piezoelectric voltages and sample thicknesses are presented. Furthermore we discuss the influence of the glue necessary to attach the VCSEL array to the piezoelectric substrate. Finally, for a first sample, the combination of (piezo-)mechanical stretching and on-chip asymmetric heating is investigated.

## 2. Simulations and Sample Preparation

Mechanical bending of a VCSEL sample is an efficient technique to obtain large birefringence splitting [7]. However, electrically driven birefringence tuning is favorable in terms of module size and fine-tuning capability. Piezoelectric transducers are a well-known manipulation tool used to induce strain in semiconductors [10, 11]. In this paper, for the first time we employ such actuators for birefringence tuning in VCSELs. To estimate the potential for strain transfer, finite-element simulations are performed with the Comsol Multiphysics software. Experimentally a VCSEL array of $1 \times 1\,\text{mm}^2$ size is attached to a piezoelectric substrate with a length of 9 mm. The relative stretching is limited to about 0.1 % (Piezo-stack PSt 150/2×3/7, Piezomechanik). In the ideal case, the strain is transferred to the VCSEL array without losses. In [7] we have reported an approximately linear increase of the birefringence splitting with increased bending. The maximum lattice expansion of about 0.4 % resulted in a birefringence splitting $B \approx 260\,\text{GHz}$. This leads to a potential birefringence splitting of about 65 GHz for strain inducing by the above piezoelectric transducers. For top-emitting VCSELs, strain relaxation takes place in the GaAs substrate below the epitaxial layers. From simulations, compared to a substrate-removed device, the strain is reduced by 19 % and 5 % for substrate thicknesses of 100 µm and 50 µm, respectively. The glue at the interface between VCSEL array and piezoelectric substrate has a thickness of about 15 µm and should theoretically have almost no influence on the transferred strain. However, quite some uncertainty exists in the actual elastic and surface properties of the glue material.

In 2016 we reported a first attempt of strain inducing in VCSELs via mechanical stretching of a piezoelectric transducer [12]. We used a $1 \times 1\,\text{mm}^2$ array of AlGaAs-based 850 nm single-mode oxide-confined VCSELs from Philips Photonics GmbH with p- and n-contacts on the top side which was glued on a piezoelectric substrate with a length of 9 mm. This is depicted in the photograph in Fig. 1 together with an image of the VCSEL unit cell as an inset.

With a sample thickness of 120 µm, including a total epitaxial layer thickness of about 8 µm on a GaAs substrate, and a stretching ratio of around 0.1 % there was no measurable change of the birefringence splitting. In this work we maximize the indirectly applied strain in the VCSEL array by reducing the thickness of the laser sample. Different VCSEL arrays with a size of $5 \times 5\,\text{mm}^2$ are cleaved from a larger sample as in [12]. We target

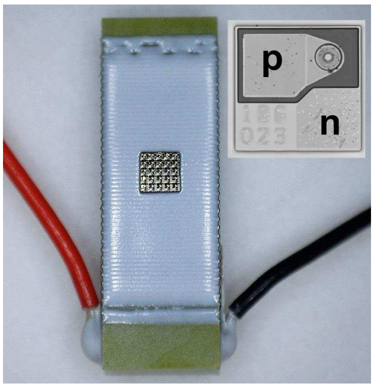


**Fig. 1:** VCSEL array of $1 \times 1\,\mathrm{mm}^2$ size glued on a piezoelectric substrate. Top view of the $165 \times 165\,\mu\mathrm{m}^2$ large VCSEL unit cell with p- and n-type top side contacts in the inset [12].

a series of measurements with sample thicknesses from 120 µm to about 20 µm in 10 µm steps. The arrays are glued upside down on a glass substrate with thermoplastic glue. To etch the GaAs substrate we use a mixture of hydrogen peroxide ($H_2O_2$) and aqueous ammonia solution ($NH_4OH$) with a pH value of 8.3. The chemical solution is sprayed at high pressure on the back side of the VCSEL array. A pre-determined etch rate serves to estimate the etch time. After etching the thinned VCSEL array is removed from the glass substrate and the final thickness is measured. We obtain samples with a minimum thickness of 28 µm. Thinner samples were too fragile and could not be handled anymore. The thinned arrays are cleaved to sample sizes of around $1 \times 1\,\mathrm{mm}^2$ to get rid of damaged material at the edges. Glueing is done with several drops of a two-component glue (EPO-TEK 353ND) that are put manually on the piezoelectric transducer with a syringe. To maximize the strain transfer, a positioning of the VCSEL array parallel to the stretching direction is necessary, which is realized by a pick-and-place machine.

## 3. Birefringence Tuning via Piezoelectric Effect

The piezoelectric substrate can be stretched by an applied voltage of up to 150 V, which could result in 0.1 % maximum expansion of the VCSEL array, disregarding the influence of the glue. The VCSEL array with minimum sample thickness of 28 µm according to Sect. 2 is investigated first. The light–current–voltage (LIV) curves and optical spectra are measured for piezo voltages $V_{\mathrm{piezo}}$ from 0 to 150 V in steps of 10 V. In addition, a measurement for a negative piezo voltage $V_{\mathrm{piezo}} = -30\,\mathrm{V}$ is done to see the effect of compression. Figure 2 shows the results for $V_{\mathrm{piezo}} = 0\,\mathrm{V}$. The threshold current is $I_{\mathrm{th}} = 0.5\,\mathrm{mA}$ at a voltage of $V_{\mathrm{th}} = 1.72\,\mathrm{V}$. At a bias current of $I = 3.5\,\mathrm{mA}$ an optical output of $P = 0.95\,\mathrm{mW}$ is reached. No change in $P$ is noticed for a stretched sample at $\hat{V}_{\mathrm{piezo}} = 150\,\mathrm{V}$. Figure 2 also includes the optical spectrum of the fundamental mode at $\hat{V}_{\mathrm{piezo}}$ as a dash-dotted line. The two peaks which can be seen in both spectra are the two orthogonal polarization states of the fundamental mode. The spectral shifts of the polarization modes under stretching are approximately symmetric. The spectra were measured with a linear polarizer suppressing the dominant polarization mode at shorter wavelength. Without

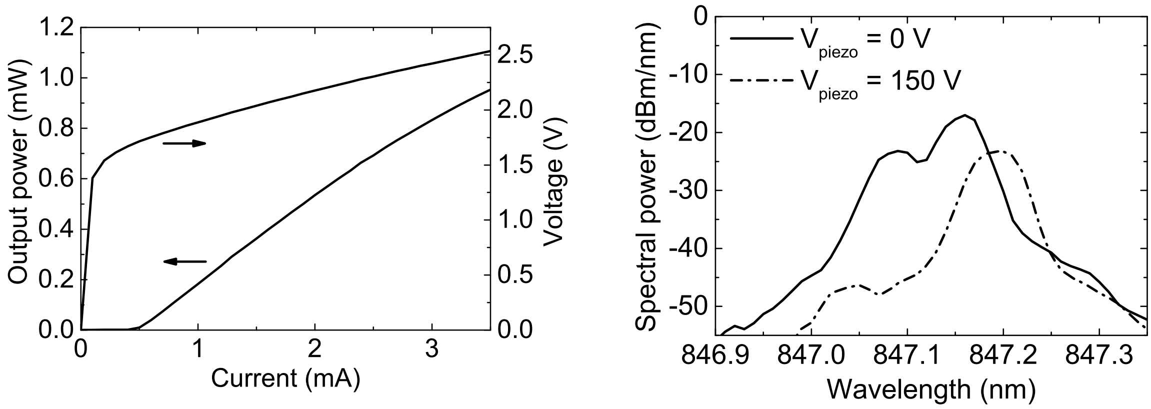


**Fig. 2:** Light–current–voltage curves of the VCSEL without applied piezo voltage (left). Optical spectra for $V_{\text{piezo}} = 0\,\text{V}$ (solid line) and 150 V (dash-dotted line) at $I = 3.5\,\text{mA}$ (right). Both measurements were done with a linear polarizer suppressing the dominant polarization mode.

polarizer, even at the maximum resolution of the optical spectrum analyzer of 0.015 nm, the weak mode would be hidden in the shoulder of the main polarization mode. Without stretching a wavelength difference of $\Delta\lambda_{0\,\text{V}} = 0.07\,\text{nm}$ is measured. This splitting indicates a built-in strain in the sample originating from the electro-optic effect [13], the fabrication process, and possible contributions from mounting and contacting. For maximum piezo voltage, $\Delta\lambda_{150\,\text{V}} = 0.16\,\text{nm}$ is obtained. The wavelength splitting corresponds to the birefringence splitting $B = \Delta\nu = c\Delta\lambda/\lambda^2$ with $c$ as the vacuum velocity of light, thus $B_{0\,\text{V}} = 29\,\text{GHz}$ and $B_{150\,\text{V}} = 67\,\text{GHz}$. The relation between birefringence splitting $B$ and voltage applied to the piezoelectric transducer $V_{\text{piezo}}$ is plotted in Fig. 3. A decrease of $B$ from $-30\,\text{V}$ to 10 V and an increase from 40 V up to 150 V are found. The maximum tuning range is $\Delta\hat{B} \approx B_{150\,\text{V}} - B_{50\,\text{V}} = (67-21)\,\text{GHz} = 46\,\text{GHz}$. The grey and black data points correspond to a dominant polarization mode at shorter and longer wavelength, respectively. Two polarization flips are observed, namely between 10 V and 40 V and at 110 V. The first flip occurs after the crossing of the modes when the long-wavelength mode is favored by the gain spectrum $g(\lambda)$. The second flip is in accordance with the shift of $g(\lambda)$ to shorter wavelengths under tensile strain [14]. The laser current and the sample temperature were kept constant, thus excluding effects of heating and associated red-shifts of the modes or the gain curve. Between about 10 V and 40 V the birefringence is below the resolution limit of the optical spectrum analyzer. As mentioned in Sect. 2, we are interested in the relation between sample thickness and birefringence splitting. Within the batch of produced samples only for four different sample thicknesses $d$ a change of $B$ was found. As can be seen in Table 1, the birefringence splitting increases from $B = 37\,\text{GHz}$ for $d = 58\,\mu\text{m}$ up to $B = 67\,\text{GHz}$ for $d = 28\,\mu\text{m}$, always at $V_{\text{piezo}} = 150\,\text{V}$. For the samples with $d = 50\,\mu\text{m}$ and $40\,\mu\text{m}$ the same birefringence splitting was measured. In our experiments we figured out that the glue plays an important role for the stress transfer from the piezoelectric substrate to the VCSEL array. As described, the glue deposition so far is a manual process and the amount of glue, which is directly related to the glue thickness, slightly differs from sample to sample.

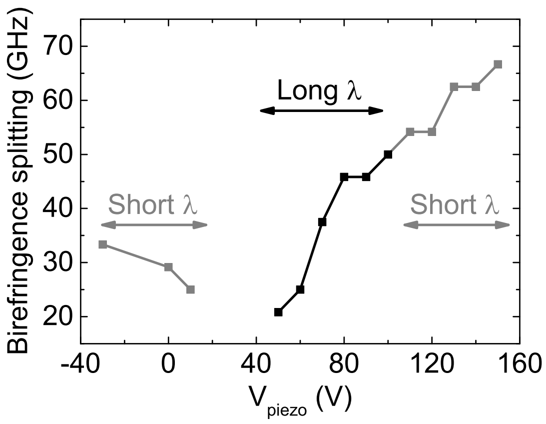


**Fig. 3:** Change of the birefringence splitting with applied piezo voltage $V_{\text{piezo}}$. Grey squares: dominance of the short-wavelength polarization mode; black squares: long-wavelength mode dominates.

**Table 1:** Birefringence splitting measured at maximum stretching of the piezoelectric transducer ($V_{\text{piezo}} = 150\,\text{V}$) for different sample thicknesses of the VCSEL array.

| Sample thickness (µm) | Birefringence splitting (GHz) |
|---|---|
| 58 | 37 |
| 50 | 54 |
| 40 | 54 |
| 28 | 67 |

## 4. Piezo-Thermal Birefringence Tuning

A VCSEL array equipped for asymmetric current-induced heating is combined with mechanical stretching using the piezoelectric effect for purely electrical piezo-thermal birefringence tuning. To incorporate strain by heating, the mesa has a keyhole-like shape with a ridge oriented parallel to one of the two preferred polarization directions. There are two bondpads on the top side connected with the ridge and the p-ring contact, respectively and a full-area back side contact. The oxide aperture diameter is around 5 µm and the ridge is fully oxidized to prevent current flow to the substrate side contact. Two electrical circuits provide a high heating current $I_{\text{H}}$ and a low laser operation current $I_{\text{L}}$ simultaneously. As shown in Fig. 4 (left), the heating current flows from the lower bondpad into the ridge to the p-ring contact and the upper bondpad. The main heating occurs in the ridge and creates an asymmetric heat gradient in the resonator. For laser operation, the current is injected in the upper bondpad and flows over the p-ring contact through the VCSEL to the back side contact. Combining this kind of VCSEL with the piezoelectric substrate, four contact needles are necessary for testing. First a VCSEL array is thinned as in Sect. 2 using wet-chemical etching until a sample thickness of 30 µm is reached. To establish a current flow for laser operation, a conductive glue (Polytec EC 101) is deposited on the piezoelectric transducer over an area slightly exceeding that of the VCSEL array. The

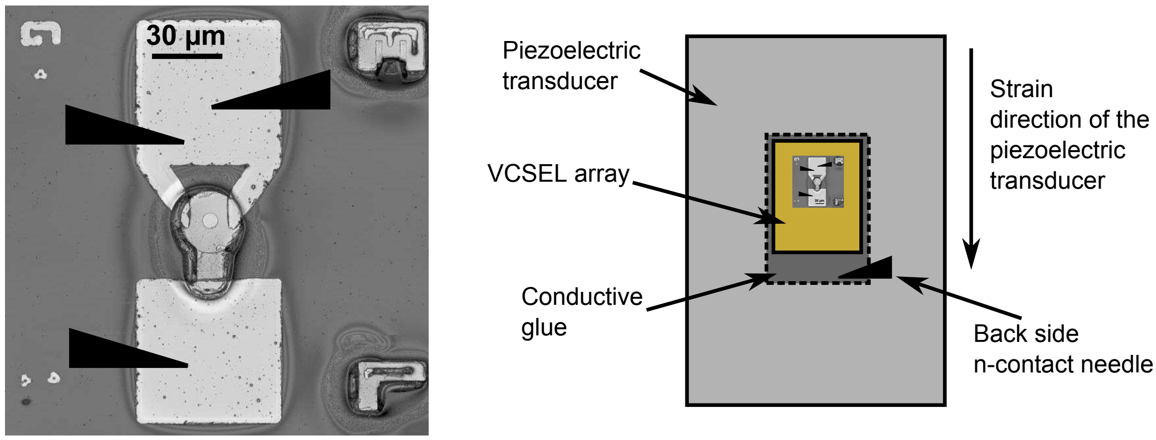


**Fig. 4:** Photograph of a VCSEL chip allowing for asymmetric thermally induced strain. Three contact needles are added for illustration (left). Schematic drawing of a VCSEL array glued on a piezoelectric transducer for piezo-thermal birefringence tuning. The image of the VCSEL unit cell shows the orientation relative to the strain direction (right).

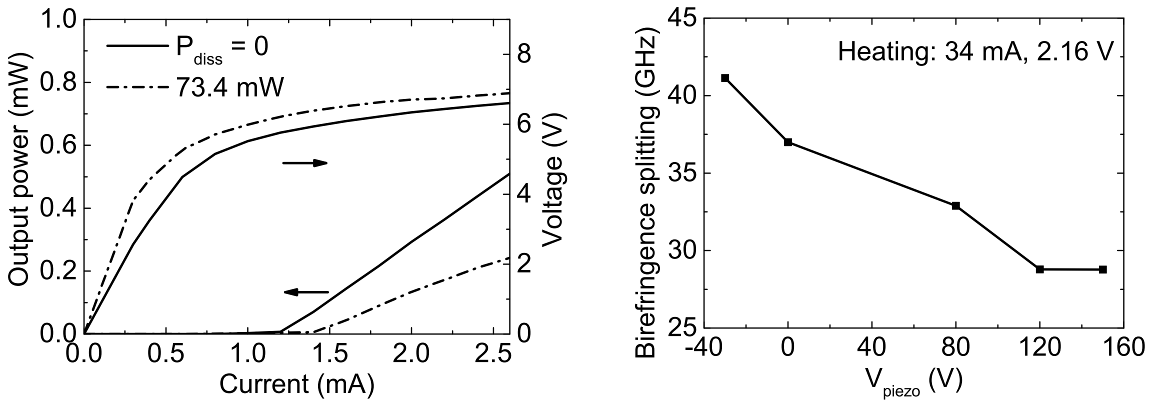


**Fig. 5:** Light–current–voltage curves of the VCSEL at 0 and 73.4 mW dissipated power (left). Change of the birefringence splitting with increasing applied piezo voltage $V_{\mathrm{piezo}}$ at a constant heating current $I_{\mathrm{H}}$ and heating voltage $V_{\mathrm{H}}$ of 34 mA and 2.16 V, respectively (right).

ridge is oriented parallel to the stretching direction of the piezo transducer. With a fourth contact needle dipped into the glue next to the VCSEL array, the electrical circuit for laser operation is established. A schematic drawing of the integrated device is depicted in Fig. 4 (right). In the experiment, the heating current $I_{\mathrm{H}}$ is set constant and the applied piezo voltage $V_{\mathrm{piezo}}$ is increased in a few large steps (−30 V, 80 V, 120 V, and 150 V). Afterwards the heating current is increased. This is done for heating currents $I_{\mathrm{H}} = 0\,\mathrm{mA}$, 20 mA, 25 mA, 30 mA, and 34 mA. The maximum value is chosen in order to prevent contact damage by overheating. Optical spectra are measured for every combination as well as the LIV curves for the different heating currents at $V_{\mathrm{piezo}} = 0\,\mathrm{V}$ to see the influence on the laser output. Figure 5 (left) shows the laser characteristics without heating (solid line) and at the peak dissipated power of $\hat{P}_{\mathrm{diss}} = \hat{I}_{\mathrm{H}} \cdot \hat{V}_{\mathrm{H}} = 34\,\mathrm{mA} \cdot 2.16\,\mathrm{V} = 73.4\,\mathrm{mW}$ (dash-dotted line). The output power at $I_{\mathrm{L}} = 2.6\,\mathrm{mA}$ is reduced by about a factor of two from $P_{0\,\mathrm{mA}} = 0.51\,\mathrm{mW}$ to $P_{34\,\mathrm{mA}} = 0.24\,\mathrm{mW}$. The threshold voltage $V_{\mathrm{th}} = 5.8\,\mathrm{V}$ can be attributed to the high back side contact resistance. In Fig. 5 (right) the birefringence splitting $B$ is displayed for increasing applied piezo voltage $V_{\mathrm{piezo}}$ at a dissipated power $P_{\mathrm{diss}} = 73.4\,\mathrm{mW}$. Surprisingly a decrease of $B$ for increased $V_{\mathrm{piezo}}$ from $B_{-30\,\mathrm{V}} = 41\,\mathrm{GHz}$ to $B_{150\,\mathrm{V}} = 32\,\mathrm{GHz}$ is measured. This behavior was verified with repeated measurements. Currently no explanation for this effect can be given.

## 5. Conclusion

We have shown mechanical stretching via piezoelectric substrates as a possibility for electrical birefringence tuning in VCSELs. For a VCSEL array with a sample thickness of 28 µm we have obtained a peak birefringence splitting of 67 GHz. We have observed an increase of the birefringence splitting with decreasing sample thickness. The glue between the sample and the piezoelectric transducer reduces the strain transferred to the laser. Automated minimum glue deposition and sample positioning are expected to improve reproducibility and to yield higher birefringence. First measurements combining thermally induced strain and piezo-mechanical stretching were done. Unexpectedly a decrease of $B$ for increased $V_{\mathrm{piezo}}$ at a constant dissipated power $P_{\mathrm{diss}}$ was found. Further investigations are in progress.

## 6. Acknowledgment

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