Vertical-Cavity Surface-Emitting Lasers With Record-High Birefringence

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Using the elasto-optic effect we increase the frequency difference between the two orthogonally polarized modes, the so-called birefringence, in standard single-mode oxide-confined GaAs-based vertical-cavity surface-emitting lasers (VCSELs). The birefringence may play an important role in the realization of ultra-fast polarization modulation for high-speed data transmission.

1. Introduction

VCSELs are used extensively today as transmitters in high-speed optical interconnects. A first generation of 28 Gbit/s devices is currently being deployed. Although digital modulation at about 50 Gbit/s has been shown [1], it is very unlikely that 100 Gbit/s signals can be generated by direct current modulation. New approaches must thus be explored to satisfy the future demand for higher data throughput. In that sense, the birefringence, i.e., the frequency difference between the two orthogonally polarized components of a VCSEL mode, may play an important role. It has been demonstrated that by optical spin injection a birefringent VCSEL can be excited to oscillations in the degree of circular polarization [2]. The oscillation frequency is very close to the birefringence. The generation of extremely fast polarization bursts is also possible [2]. It is thus of interest to tailor VCSELs to exhibit a maximum amount of birefringence. Contributions to the birefringence are geometrical anisotropies, the electro-optic effect in the cavity, and incorporated strain [3], where the latter is the strongest.

2. Generation of High Birefringence

To get a high birefringence we manipulate the lattice structure of a VCSEL via mechanically induced stress. With this technique, Panajotov et al. [3] have shown that it is possible to increase the birefringence up to 80 GHz. To reach a maximum effect, the VCSEL should be bent in a direction coinciding with one of the two preferred polarization directions. Such bending changes the crystal structure of the VCSEL in one direction, which results in an anisotropic change of the refractive index $\bar{n}$. This is known as the elasto-optic effect. A modified $\bar{n}$ is seen as a change in the emission wavelength λ. From the resonance condition of the laser one expects $\Delta\lambda = \lambda \cdot \Delta\bar{n}/\bar{n}$ or $\Delta\nu = \nu \cdot \Delta\bar{n}/\bar{n}$ for the oscillation frequency $\nu = c/\lambda$ with the vacuum velocity of light c.

Another approach was shown by Jansen van Doorn et al. [4], namely an external heat source can be used to manipulate the birefringence. In this case a Ti-sapphire laser beam is focused close to the VCSEL and the induced heat deforms the crystal structure. The change of birefringence (less than 3 GHz in [4]) is substantially smaller compared to the use of a mechanical bending device due to the much lower induced stress.

3. Experimental Results

To increase the birefringence beyond 100 GHz we employ a custom-made bending device sketched in Fig. 1. It ensures an exact positioning of the VCSEL sample.

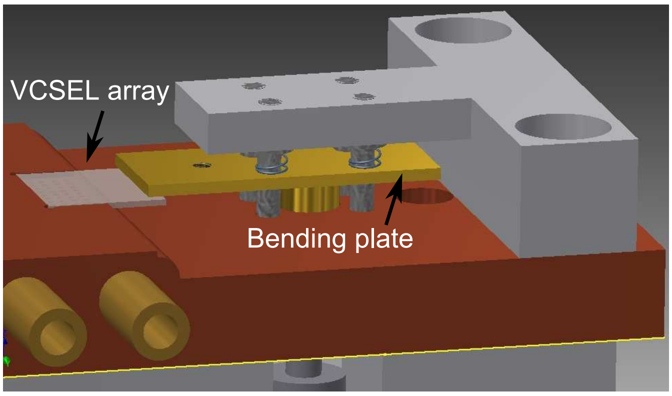

Fig. 1: Drawing of a bending device with bending plate and VCSEL array sample (after [5]).

The sample is a VCSEL array of $10 \times 10\,\mathrm{mm}^2$ size which can be fixed via vacuum in a slot. The bending plate is in a stable horizontal position and can be moved up and down by a micrometer screw. We use a contact current measurement to verify the starting point, just before bending. With this defined starting point and the known step size of the micrometer screw, the bending distance is well under control. In combination with the wavelength difference which we obtain from the spectral measurements we can determine the relation between birefringence and bending distance. For our measurements we contact one VCSEL and bend the sample (grown on (100)-oriented GaAs) along the $[0\bar{1}\bar{1}]$ or $[01\bar{1}]$ crystal direction with a step size of 10 µm. For every step we measure the light–current–voltage (LIV) curves and the optical spectrum. At the end of the measurement series we rotate the VCSEL array by 90°, contact the same device and repeat the procedure by bending along the other crystal direction.

A single VCSEL on the sample with both crystal directions marked is depicted in Fig. 2 (left). Scratches on the bondpad originate from the contact needle. The ground contact is at the bottom of the GaAs substrate. Figure 2 (right) displays the LIV curves of the standard single-mode oxide-confined VCSEL with about 4 µm active diameter. The threshold current and voltage are 0.54 mA and 1.84 V, respectively. An optical output power of 1 mW is reached at about $I = 2$ mA current. The higher-order transverse mode is suppressed by ≈ 37 dB at $I = 2.1$ mA. With the measured wavelength difference in the spectra taken without a polarizer we can calculate the frequency difference $\Delta\nu$, which is equal to the birefringence $B = \Delta\nu$.

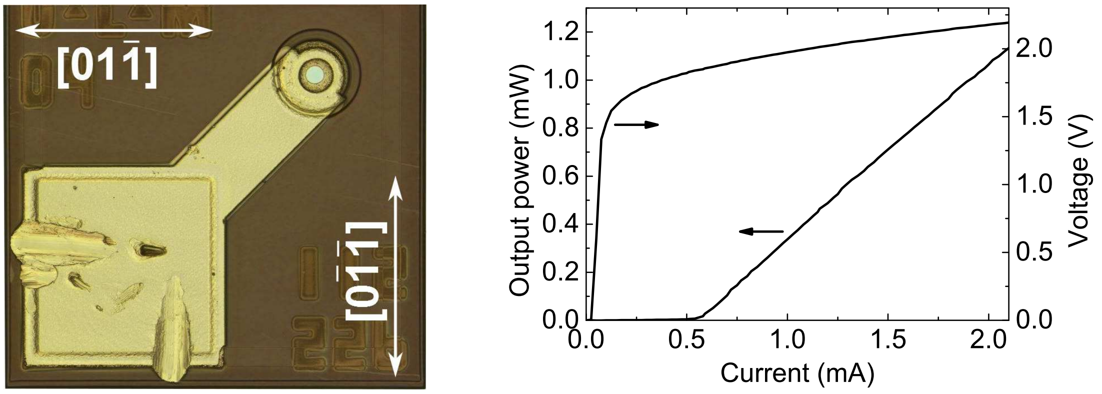

Fig. 2: VCSEL chip with an 80 × 80 µm^2 size bondpad and the output aperture in the upper right corner. $[01\bar{1}]$ and $[0\bar{1}\bar{1}]$ are the crystal directions and preferred polarization directions (left). Operation curves of the VCSEL under investigation (right).

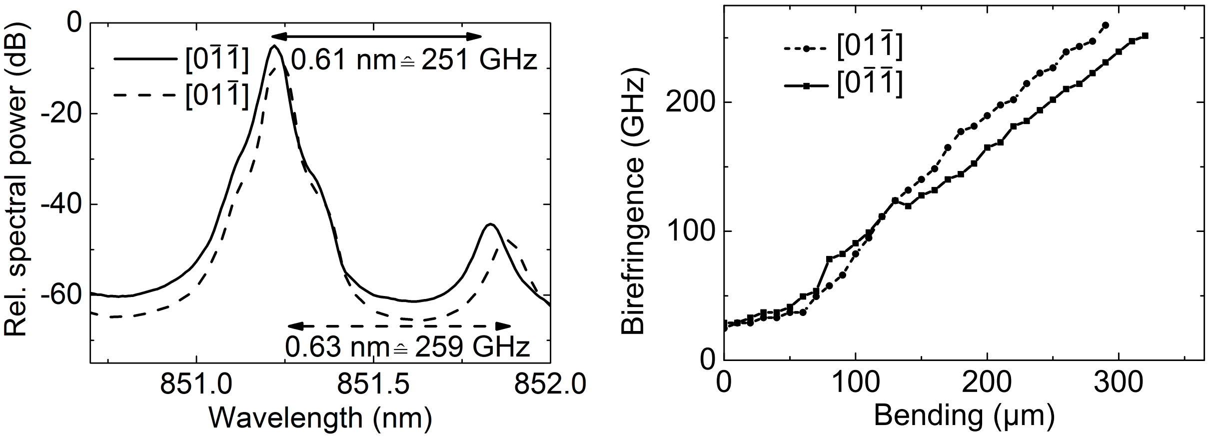

Fig. 3: Spectra of the fundamental mode (at $I = 2.1\,\text{mA}$) for maximum bending in the $[0\bar{1}\bar{1}]$ and the $[01\bar{1}]$ crystal directions. Birefringence versus applied bending in both crystal directions (right).

In Fig. 3, the spectra of the fundamental mode under maximum bending and the relation between bending distance and birefringence are shown. The spectra look similar for both bending directions. We have reached a birefringence of 259 GHz for bending along the $[01\bar{1}]$ crystal direction with a maximum bending distance $\hat{L}_\text{b}$ of 290 µm and $B = 251\,\text{GHz}$ for the $[0\bar{1}\bar{1}]$ crystal direction with $\hat{L}_\text{b} = 320\,\mu\text{m}$. The measured birefringence is more than a factor of three higher than the previous record [3]. There is an approximately linear relationship between birefringence and bending distance in Fig. 3 (right). This behavior is similar for both crystal directions. The second measurement (in $[01\bar{1}]$ direction) after rotating the sample has only $\hat{L}_\text{b} = 290\,\mu\text{m}$. At this point the sample broke into two pieces.

4. Conclusion

With an experimentally obtained value of more than 250 GHz, we have shown that it is possible to increase the birefringence of a VCSEL via mechanically induced stress far beyond the previous record. The planned experiments in collaboration with the group of Dr. N.C. Gerhardt and Prof. M.R. Hofmann at Ruhr University Bochum [2] will show if spin-induced oscillations in the degree of circular polarization with correspondingly high frequencies can be induced.

5. Acknowledgment

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