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ABSTRACT
We investigate and compare the intensity and polarization dynamics in a vertical-cavity surface-emitting laser (VCSEL) with a monolithically integrated, electrically controlled birefringence tuning mechanism. The influence of the bias current on the polarization dynamics is investigated over a large range of birefringence values. Bias current tuning toward low values and simultaneous maximization of the resonance frequency is an important strategy to optimize the spin-VCSEL toward energy-efficient operation. A polarization dynamics resonance tuning range from a few GHz up to the maximum frequency of 36 GHz was achieved, and polarization dynamics at maximum frequency are demonstrated at minimum bias current and at high temperatures of approximately 70 °C. We propose a strategy for data communication with low energy consumption and low cooling effort.

Spin-lasers, in particular spin-vertical-cavity surface-emitting lasers (spin-VCSELs), have experienced increasing research interest in the last few years. They have been investigated for threshold reduction or spin-filtering and amplification. However, a major advantage in comparison to their non-spin-polarized counterparts is the possibility to control the polarization state of the light output dependent on the spin-polarization of the carrier system, resulting in an important feature: controlled ultrafast polarization dynamics. While the conventional intensity resonance frequencies are in the range of 35 GHz, we have recently been able to experimentally demonstrate ultrafast polarization dynamics and resonance frequencies above 200 GHz in birefringent spin-VCSELs. This was obtained by increasing the birefringence in the cavity via the elastooptic effect by applying external strain. Such extremely fast dynamics can be of great use for future optical data transmission systems. The resonance frequency for intensity as well as polarization modulation is strongly linked to the usable bandwidth for optical data transmission. In the case of intensity dynamics, the resonance frequency can be maximized by increasing the photon density via raising the bias current. Despite the increase in possible data rates obtained, the inseparably linked increase in power consumption caused by the higher bias current can be considered as detrimental and limits the obtainable maximum dynamics resonance frequency \( f_R \) for intensity modulation. In contrast to intensity dynamics, the polarization dynamics resonance frequency \( \tilde{f}_R \) of spin-VCSELs is mainly determined by the birefringence and previous work suggests that it is almost independent of the bias current. As a consequence, the shape and bandwidth of the polarization modulation response is expected to be almost independent of the bias current, too. This assumption is supported by recent experimental findings in 1.5 μm VCSELs by Yokota et al. for three values of the pumping current. The bias independence of \( \tilde{f}_R \) and the potentially possible operation close to threshold may provide a path toward ultralow power consumption of optical transmitters utilizing spin-VCSELs with high birefringence and low bias current, only limited by the laser threshold and by the required optical output power for the transmission...
line. As polarization dynamics seem quite independent of the bias current, it might be expected that they are insensitive to temperature changes as well. It may even be possible to get rid of any temperature controlling mechanism in an application context, further reducing energy consumption and complexity. To prove all this, a detailed study is necessary.

In this work, we conduct a systematic experimental comparison of the conventional intensity dynamics and the spin-controlled polarization behavior of a spin-VCSEL for varying bias current, birefringence, and effective device temperature. For this study, we utilize a custom 850 nm VCSEL with electrically tunable cavity birefringence and temperature, allowing the control of all parameters necessary for our study. A fine-tuning of the birefringence is possible over a wide range. The device is used as a conventional laser when driven without spin-injection and as a spin-laser when additional optical spin-injection is applied. In this study, we analyze a frequency range up to 36 GHz, limited only by the electrical tuning mechanism to control the birefringence in the investigated device.

Three key insights are gained in this work: (i) We show the static polarization behavior for the entire bias pumping range from threshold to high pumping regimes of approximately five times threshold, which has not yet been shown for this type of device. We find polarization switching (PS) between the orthogonal linearly polarized fundamental transverse modes, strongly dependent on both the electrically controlled birefringence and the bias current. (ii) We investigate resonant polarization dynamics in this unique device and demonstrate experimentally for the full parameter range of bias currents and obtainable birefringence values that the fast polarization dynamics does not rely on a specific operation point and can be observed even at operation close to threshold. All together, we present the required systematic study to investigate pumping influences in detail, especially close to threshold. (iii) Exploiting the heating principle of operation of the birefringence tuning mechanism, we conduct a study of the temperature dependence of polarization dynamics and observe dynamics at high temperatures, showing no detrimental influence on the polarization dynamics resonance frequency.

The 850 nm oxide-confined AlGaAs-based VCSEL device used in this study was developed for the scope of an integrated birefringence tuning mechanism in order to investigate the polarization dynamics in this study. In short, the VCSEL mesa is extended with a ridge to a keyhole shape. By driving a current through the ridge, an asymmetrical heating is obtained. Through the elasto-optic effect, this results in a reversible tuning of the birefringence splitting in the asymmetric heating region of a few GHz up to several tens of GHz. More details on the device can be found in previous work.\textsuperscript{18,19}

To investigate the static polarization behavior without spin-injection, the VCSEL is driven with a pumping current \(I_{\text{bias}}\) starting at the threshold current of approximately 0.4 mA and going up to its maximum rating of 2 mA. This measurement is repeated for each value of the birefringence tuning current \(I_{\text{heat}}\) starting from 10 mA up to 30 mA. The lower limit is set in order to obtain splittings of at least some GHz, which is necessary to resolve the dynamic signal in the 800 ps-long time window of the streak camera later on. The upper limit was chosen to remain sufficiently below the damage threshold. The VCSEL emits its fundamental mode in the typical VCSEL polarization behavior.\textsuperscript{20} The change of sign of \(S_3\) indicates a polarization switching (PS) point, where the overall polarization changes from one of the two linear orthogonally polarized VCSEL modes to the other.\textsuperscript{19} Only very close to the threshold current, the absolute value of \(S_1/S_0\) is reduced. The trace of the PS points shows a horseshoe shape, resulting in no, one, or two PS points when increasing \(I_{\text{heat}}\) at a constant \(I_{\text{bias}}\). The PS points are relevant for the polarization dynamics as they define different stability regimes with varying oscillation amplitude damping.\textsuperscript{18} Evidence of the polarization switching point in the polarization dynamics can be found in Figs. 2(b), 2(c), and 4, as described in detail later. Due to the heating necessary to control the birefringence, the threshold current experiences a small increase of not more than 0.1 mA. This has been considered where relevant. We characterize the heating by measuring the wavelength of the lasing mode. The resulting wavelength shift dependent on \(I_{\text{heat}}\) and \(I_{\text{bias}}\) is measured. From the lowest wavelength of 845.52 nm at minimum bias current and heating current to the maximum wavelength of 849.03 nm, a red-shift of approximately 3.51 nm is observed. The temperature-dependent wavelength shift typically amounts to a rate of 0.07 nm K\(^{-1}\) for GaAs VCSELs.\textsuperscript{21}

The maximum redshift at \(I_{\text{bias}} = 2.0 \text{ mA}\) and \(I_{\text{heat}} = 30 \text{ mA}\) results in a lower bound estimation of the maximum temperature of approximately 70°C, given that the initial temperature was close to room temperature [see Fig. 1(b)]. The birefringence-induced mode splitting at these parameters reaches approximately 40 GHz or 96 pm and is thus also shifting the mode position. However, the corresponding maximum error of 96 pm/(0.07 nm K\(^{-1}\)) = 1.4 K is negligible compared to the absolute temperature shift.

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{fig1.png}
\caption{Measured normalized Stokes parameter \(S_3\), depending on heating current \(I_{\text{heat}}\) and pumping current \(I_{\text{bias}}\) (a). Operation condition dependent cavity temperature determined via emission wavelength shift (b).}
\end{figure}
Now we focus on the dynamics of the VCSEL. For our experiments, we employ a hybrid pumping scheme, consisting of a spin-unpolarized electrical bias pumping ($I_{\text{bias}}$) and an optical pumping with Ti:sapphire laser pulses at 760 nm wavelength with an average power of 8 mW. The pumping pulses are circularly polarized. According to the optical selection rules, this leads to changes in both the total carrier density and the carrier spin-polarization. The total carrier density change results in an intensity relaxation oscillation (with characteristic frequency $f_R$), giving evidence of the intensity dynamics resonance frequency. The change of the spin-polarization induces an oscillation of the circular polarization degree $P_C$. Generally speaking, such polarization oscillations can be understood as a superposition of two linear orthogonally polarized modes becoming active simultaneously. Due to their birefringence-induced frequency splitting, an envelope oscillation occurs with the frequency of the splitting. This corresponds to the polarization dynamics resonance frequency $f_{R_{\text{polar}}}$, which can be tuned by the birefringence. The VCSEL intensity and polarization dynamics are analyzed with the previously mentioned Stokes polarimeter and the streak camera. A sketch of the setup is depicted in Fig. 2(a). More details on the setup and the fundamental polarization behavior can be found in previous publications.\textsuperscript{11,12}

As a first step, we present the influence of the PS point on the dynamics. For a heating current of $I_{\text{heat}} = 24$ mA, a full sweep of the bias current results in operation both below and above a PS point, which is at around $I_{\text{bias}} = 0.95$ mA (type I: switching from the higher to lower frequency mode with increasing $I_{\text{bias}}$). An oscillation in the circular polarization degree can be observed, changing its sign at the PS point, as depicted in Fig. 2(b). In comparison to the coordinates in Fig. 1(a), we find a slight deviation, which is expected due to the additional influences of the optical pumping. Furthermore, the damping and amplitude of the oscillation changes with $I_{\text{bias}}$. Smaller damping can be observed at currents in the vicinity of the PS point. Higher amplitudes can be observed, especially at smaller pumping currents. However, the signal amplitude is not significantly affected by changing the bias current over the entire range: At a bias current close to threshold, the highest value of $P_C = 52\%$ could be obtained ($P_C = 46\%$ for $I_{\text{bias}} = 2.0$ mA). Therefore, driving polarization dynamics close to threshold, around a PS point, and at maximum bias current is reasonable. Figure 2(c) depicts the normalized amplitude of a fast Fourier transform (FFT) of the $P_C$ signal in Fig. 2(b). The dominating frequency of about 20 GHz in the spectra coincides with the birefringence at the chosen $I_{\text{heat}}$ and changes only slightly with $I_{\text{bias}}$. The minor variation can be attributed to the additional heating induced by $I_{\text{bias}}$, giving rise to a comparably small change in birefringence. It should be noted that the FFT shows a change in amplitude at the PS point, which can be attributed to changes of both the oscillation amplitude and the oscillation damping. Choosing the point of operation with respect to PS points, which can be extracted from Fig. 1(a), can be a helpful tool to optimize the dynamics for a desired application. For optical data communication, an amplitude of several tens of percent seems to be adequate, as also for intensity modulation only a fraction of the absolute amplitude is modulated and sufficient to be detected.
Now, we investigate the dynamics for the entire parameter range of $I_{\text{heat}}$ and $I_{\text{heat}}$ introduced earlier in order to compare intensity and polarization dynamics for all parameter combinations. It is well known that the intensity resonance frequency can be increased by raising the photon density, which can be obtained by increasing the pumping current.\(^{17}\) This effect can be observed in Fig. 3(a). Here, for low $I_{\text{heat}}$, the intensity resonance oscillation frequency $f_R$ varies from $f_R \approx 4 \, \text{GHz}$ close to threshold up to $f_R \approx 12 \, \text{GHz}$ at the maximum pumping current, which is close to the highest achievable $f_R$ in our device. The polarization dynamics resonance frequency in the same parameter range is depicted in Fig. 3(b). In contrast to the intensity relaxation oscillation, the resulting polarization resonance frequency is nearly constant (deviations below 1.5 GHz) for the entire pumping current range. The small dependence on pumping current is attributed to heating effects. As already mentioned, the polarization dynamics resonance frequency is determined by the birefringence-induced mode splitting, which is mainly controlled by the heating current $I_{\text{heat}}$. It is found that $f_R$ can be controlled between 5 GHz and 40 GHz in the device. While $f_R$ increases with $I_{\text{heat}}$, $f_R$ decreases due to the increasing device temperature. This shows that $f_R$ is insensitive to temperature effects. We note that fast dynamics can already be attained close to threshold, do not require a high pumping current, and thus can be very energy-efficient. Figure 3(b) proves the tunability of the polarization oscillation frequency via the heating current for bias points close to threshold.

We furthermore plot the resulting polarization oscillation frequency over the heating power in Fig. 4, revealing a roughly linear dependency and a negligible influence of $I_{\text{bias}}$. This supports the observation made earlier for the static birefringence-induced mode splitting.\(^{17}\) For comparison, the dependence on the heating current is depicted in the inset. However, $f_R$ shows a small step close to both PS points (at around $P_{\text{heat}} = 15 \, \text{mW}$ and $P_{\text{heat}} = 55 \, \text{mW}$). The change in $f_R$ can be attributed to the nonlinear birefringence, which introduces a step change in the effective birefringence at a PS point. This leads to a change in the oscillation frequency. It should be noted that the positions of the PS points are slightly shifted in comparison to the measurement shown in Fig. 1(a) due to the additional optical spin-injection and associated heating applied here.

This experimental demonstration of close-to-threshold dynamics shows the potential for ultrafast low-power operation of spin-VCSELs for the purpose of short-haul optical data communication. Utilizing spin-VCSELs for data transmission requires a continuous spin and polarization modulation in order to encode binary data in the circular polarization degree. In an advantageous manner, this can be obtained by replacing the optical spin injection used here by an electrical spin injection mechanism (e.g., Ref. 24), which is, however, not yet available for VCSELs at room temperature. Still, alternative concepts are under development.\(^{25,26}\) Furthermore, in the case of polarization modulation, the polarization dynamics must be appropriately damped. The damping is mainly determined by the dichroism and is found to be appropriate for high-speed data transmission in spin-VCSELs. Continuous polarization modulation and the influence of dichroism are discussed in Ref. 12.

Furthermore, alternative methods to induce birefringence, which do not involve additional power consumption, can be incorporated. An extremely high birefringence of more than 250 GHz can be introduced using external mechanical straining mechanisms.\(^{11,27,28}\) For future applications, a highly integrated on-chip method to introduce high birefringence is necessary, whereas a tuning mechanism can be omitted. We recently presented a birefringent VCSEL with about 100 GHz mode splitting using a surface grating structure.\(^{27}\) Considering, for example, the extremely high birefringent spin-VCSEL we demonstrated,\(^{17}\) when used with the low pumping condition of 1.5 times threshold current demonstrated in this work, a heat-to-data ratio of 3.8 fJ/bit at 240 Gbit/s can be expected for polarization-based data transmission. In a VCSEL optimized for low power operation, 56 fJ/bit at 25 Gbit/s has been obtained with intensity-based operation at a bias current of 7 times threshold.\(^{30}\) This demonstrates the tremendous advantage of being able to drive the spin-VCSEL close to threshold when using polarization dynamics. Furthermore, this work shows that highest dynamics can also be obtained at high temperatures, which opens up the field of low-power and high-temperature operation, potentially further reducing the cooling effort in data centers.

In conclusion, we have investigated the static and dynamic polarization behavior of a VCSEL device with electrically tunable birefringence for the full range of bias pumping currents. We find that even for close-to-threshold operation and at high temperatures, fast polarization dynamics with good signal strength can be
obtained. This demonstrates the potential of spin-VCSELs for ultrafast and ultra-low power operation for optical data communication, even without temperature controlling mechanisms.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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