Spin-Lasing in Bimodal Quantum Dot Micropillar Cavities

Niels Heermeier, Tobias Heuser, Jan Große, Natalie Jung, Arseny Kaganskiy, Markus Lindemann, Nils C. Gerhardt, Martin R. Hofmann, and Stephan Reitzenstein*

Spin-controlled lasers are highly interesting photonic devices and have been shown to provide ultrafast polarization dynamics in excess of 200 GHz. In contrast to conventional semiconductor lasers their temporal properties are not limited by the intensity dynamics, but are governed primarily by the interaction of the spin dynamics with the birefringent mode splitting that determines the polarization oscillation frequency. Another class of modern semiconductor lasers are high-\(\beta\) emitters, which benefit from enhanced light–matter interaction due to strong mode confinement in low-mode-volume microcavities. In such structures, the emission properties can be tailored by the resonator geometry to realize for instance bimodal emission behavior in slightly elliptical micropillar cavities. This attractive feature is utilized to demonstrate and explore spin-lasing effects in bimodal high-\(\beta\) quantum dot micropillar lasers. The studied microlasers with a \(\beta\)-factor of 4\% show spin-laser effects with experimental polarization oscillation frequencies up to 15 GHz and predicted frequencies up to about 100 GHz, which are controlled by the ellipticity of the resonator. These results reveal appealing prospects for very compact, ultrafast, and energy-efficient spin-lasers and can pave the way for future purely electrically injected spin-lasers enabled by short injection path lengths.

1. Introduction

A high transmission bandwidth and stable transmission for optical communication systems are decisive for the Internet structure and the key to global digitization.\[1\] With Internet traffic and computing power increasingly concentrated in high-scale data centers due to the growing importance of cloud computing services, short-range optical communication systems play an important role.\[11\] These systems are mainly based on direct current modulated semiconductor lasers such as vertical-cavity surface-emitting lasers (VCSELs). However, the small-signal modulation bandwidth of VCSELs is limited to values below 40 GHz,\[2,3\] mainly due to the coupled carrier-photon dynamics in the resonator and additional parasitic electrical effects. It is highly questionable whether this technology will meet future bandwidth requirements. To close this gap, new concepts for ultrafast short-range communication systems with higher modulation bandwidth are required. In this regard spin-lasers, such as spin-polarized VCSELs (spin-VCSELs), have recently proven to be a promising new device technology.\[4–6\] In these devices, the polarization state of the laser emission can be controlled by the spin state of the carriers and the transfer of angular momentum between carrier spin and photon spin plays a decisive role in their dynamical behavior.\[6\] In fact, the dynamics of the coupled spin system are usually decoupled from the intensity dynamics and can be much faster than those. Interestingly, the modulation bandwidth of spin-lasers can be directly controlled and increased by the mode splitting between the two orthogonal linearly polarized laser modes, e.g., by inducing birefringence into the resonator\[7–9\] Frequencies >200 GHz have been demonstrated following this concept recently which potentially provide a single channel data transmission rate of more than 240 Gbit s\(^{-1}\).\[5\] Another important advantage of spin-VCSELs is their potential for very low power consumption. In contrast to conventional lasers, the ultrafast modulation response in spin-lasers can be obtained for low carrier densities even close to threshold and is not severely affected by high temperatures.\[5\] This opens up new possibilities for energy-efficient high-speed communication systems, which are important for reducing the currently soaring energy consumption of data centers worldwide.\[1\]

The need for novel energy-efficient devices can also be addressed by cavity-enhanced nano- and microlasers which have received significant scientific attention in recent years and which promise not only small size footprint but also strongly decreased threshold pump powers due to pronounced light–matter interaction.\[10\] In fact, in such devices pronounced light–matter interaction in the frame of cavity quantum electrodynamics

N. Heermeier, T. Heuser, J. Große, A. Kaganskiy, S. Reitzenstein
Technische Universität Berlin
Hardenbergstraße 36
Berlin 10623, Germany
E-mail: stephan.reitzenstein@physik.tu-berlin.de
N. Jung, M. Lindemann, N. C. Gerhardt, M. R. Hofmann
Lehrstuhl für Photonik und Terahertztechnologie
Fakultät für Elektrotechnik und Informationstechnik
Ruhr-Universität Bochum
Universitätsstraße 150
Bochum 44780, Germany

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/lpor.202100585
DOI: 10.1002/lpor.202100585
modesplittingintheellipticityofthepillarcross-sectionfordifferentpillardiameters. flip model, [6, 17] which is a commonly used tool to predict spin-sults are supported by theoretical modelling based on the spin- associated spin-oscillation frequencies. The experimental rede- for highly compact, fast and energy efficient spin-lasers thineed to push the spin and polarization dynamics to highest essary to push the spin and polarization dynamics to highest

(cQED) leads to a high fraction (β) of spontaneous emission coupled into the lasing mode, thus reducing the threshold pump powers by orders of magnitude in comparison to standard semiconductor lasers. [11] Moreover, high-β lasers are highly interesting from the fundamental science point of view because they allow one to explore the physical and technological limits of semiconductor lasers at the crossroads between classical and quantum physics. [12] Quantum dot (QD) micropillars are a very interesting type of high-β microlasers which often show a strong bimodal behavior due to a (usually unintentional) asymmetry of the pillar’s cross-section. [13] This leads to pronounced temporal mode switching and intriguing nonlinear dynamics effects, [14] such as complex injection locking [15] and zero-lag synchronization, [16] under external feedback or mutual coupling of micropillar cavities. Their bimodal behavior together with directional normal to the sample surface makes them highly interesting as a novel class of spin-lasers. In fact, the integration of ultrafast spin and polarization dynamics with microcavities in bimodal QD-micropillar lasers is a novel concept combining the advantages of two emerging technologies. In particular using elliptically shaped bimodal micropillar cavities provides a perfect design parameter to induce the required mode splitting between orthogonally polarized laser modes, necessary to push the spin and polarization dynamics to highest frequencies.

In this work, we realize bimodal quantum dot micropillar cavi- ties and we explore their potential to act as high-speed spin-lasers with well-controlled emission properties. We utilize the fact that the spectral splitting of the fundamental emission mode can be controlled by the ellipticity of the pillar’s cross-section which in turn controls the spin-oscillation frequency of these high-β microlasers. By implementing ellipticities ε of up to 31%, we realize mode splittings ΔE (Δf) of up to 84 μeV (≈21 GHz) to control the associated spin-oscillation frequencies. The experimental results are supported by theoretical modelling based on the spin- flip model [6, 17] which is a commonly used tool to predict spin-VCSEL behavior. Our work provides first insight into spin-lasing properties of high-β microlasers and has high potential to pave the way for highly compact, fast and energy efficient spin-lasers in the future.

2. Device Fabrication and Basic Emission Properties of Bimodal QD-Microlasers

2.1. Device Fabrication

The bimodal micropillars under study are based on an Al- GaAs/GaAs planar microcavity structure with a single layer of InGaAs QDs embedded in the central one-λ thick GaAs cavity. Using high-resolution electron beam lithography and plasma enhanced reactive ion etching we patterned arrays of micropillars with elliptical cross-section (please see Experimental Section for details on the sample growth and device fabrication). To achieve the required bimodal emission behavior and to study the influence of the device geometry on the mode splitting we realized micropillars with ellipticities ε = \sqrt{b/a} – 1 up to 31%, where a (b) denotes the short (long) axis of the pillar’s cross-section. Figure 1a shows a scanning electron microscope (SEM) image of three micropillars with a long axis of 4 μm and an ellipticity of about 10%. The structures show vertical sidewalls with rather small surface roughness. We etched about 1/3 of the lower distributed Bragg reflector (DBR) which is sufficient to achieve the desired lateral mode confinement and to maintain high quality (Q) factors in the range of 10,000. [18]

2.2. Basic Emission Properties

The emission properties of the QD micropillars were studied by high-resolution micro-photoluminescence (μPL) spectroscopy at low temperature (10 K) (see Experimental Section for details on the experimental setup). A μPL spectrum of a micropillar with a long axis of 5.6 μm and an ellipticity of about 10% is presented in Figure 1b. We observe two linearly polarized components of the fundamental emission mode with a spectral splitting ΔE of (41 ± 4) μeV induced by an elliptical cross-section. To obtain a better understanding on the influence of the intentionally intro- duced ellipticity we evaluated the resulting splitting ΔE of the fundamental mode, which we also utilize as a measure for the effective birefringence, in dependence of the pillar diameter and the ε parameter. Figure 1c shows the measured mode splitting
The intensity is given in terms of average photon number $p$ which was obtained by fitting the experimental data. While the strong mode (SM) shows the typical s-shaped power dependence with some deviations in the high-power regime, the weak mode (WM) shows a drop in intensity at about 5 mW and a revival above 8 mW. The slight oscillatory behavior of mode intensity in the high excitation regime is explained in terms of gain competition of the two modes for the common QD gain. A fit (blue curve) to the data of the two modes for the common QD gain. A fit (blue curve) to the data of the SM yields a $\beta$-factor of 4% and a threshold pump power of 2.1 mW, where the dashed horizontal line indicates $p = 1$ defined as the threshold photon number, see Experimental Section for details. The emission linewidth of both modes decreases strongly above 1 mW input power which confirms the onset of coherence at threshold due to enhanced temporal coherence in the lasing regime. Interestingly, the intensity fluctuations in the high excitation regime are also reflected in the emission linewidths and lead to deviations from the resolution limit for input powers exceeding 6 mW.

3. Spin-Lasing of Bimodal Quantum Dot Microlasers

3.1. Time Resolved Detection of Polarized Emission

A central aspect of this work is the demonstration of spin-lasing in high-$\beta$ microlasers. For this purpose, we pumped the micro-laser discussed above optically by a CW laser at 785 nm, i.e., non-resonantly above the GaAs bandgap, at an excitation power of $\approx15$ mW, which is about seven times the threshold of 2.1 mW. This leads to an excitation of spin unpolarized carriers. For the injection of spin-polarized carriers and to access the dynamical properties, we applied in addition pulsed (ps-pulses at 80 MHz repetition rate) circularly polarized laser light with adjustable average power in the range of up to 10 mW at the sample surface. The light of the pulsed laser with a wavelength of 905 nm is resonant with wetting layer states of the QDs. Please see Experimental Section for details on the experimental setup.

Polarization resolved measurements of emission from the bimodal QD micropillar using a streak camera with 4 ps time resolution allowed us to determine the time dependent emission in left and right circular polarizations denoted as $S^+$ and $S^-$, respectively. Figure 3a depicts the time resolved polarized emission detected from the QD-micropillar discussed above with a diameter of 5.1 $\mu$m and a mode splitting $\Delta E$ of $(41 \pm 4)$ $\mu$eV. The micro-laser was driven with 14.98 mW CW excitation (at 785 nm) and additional pulsed circularly polarized excitation with 2.5 mW (at 905 nm). Upon excitation with the laser pulse at zero delay, both $S^+$ (red trace) and $S^-$ (black trace) rise and show an oscillatory behavior with increasing time delay. The associated oscillations in the circular polarization modes can clearly be resolved for delays larger than 100 ps. They show the expected antiphase behavior and are damped with a time constant of $(0.19 \pm 0.01)$ ns as determined from the sinusoidal fitting of the S3 parameter discussed in the next section.

3.2. Time Dependent Spin-Polarization Degree

To obtain further insight into the spin-lasing properties of the QD-micropillar laser we determined the polarization degree of emission in terms of the S3 Stokes parameter, which is defined as $S3 = (S^+ - S^-)/(S^+ + S^-)$. The resulting time dependence of the S3 parameter after FFT filtering as indicated by the grey area in the inset of Figure 3a is depicted in Figure 3c for a pulsed laser power of 2.5 mW (black trace). The excitation with pulsed...
Figure 3. Spin polarized emission and spin-oscillation of bimodal QD micropillar lasers with a mode splitting $\Delta E$ of $(41 \pm 4) \mu eV$ and a diameter of 5.1 $\mu$m recorded at pulsed laser power of 2.5 mW (CW power: 14.98 mW). a) Time transient of the left (red) and right (black) circular polarized emission of the microlasers. b) Simulation of the time transients of the left (red) and right (black) circular polarized emission of the microlaser utilizing the spin-flip model. CW offsets have been subtracted for presentation purposes. c) $S_3$ parameter calculated from the data presented in panel (a) after FFT analysis and applying a filter as indicated by the grey area in the inset. Fitting the data (dots) with a damped sinusoidal function (red, solid line) yields a polarization-oscillation frequency of $(10.4 \pm 0.1)$ GHz in agreement with the corresponding FFT spectrum presented in the inset of panel (a). The decay constant of the $S_3$ oscillation is $(0.20 \pm 0.01)$ ns. d) $S_3$ parameter calculated from the data presented in panel (b).
of the mode splitting $\Delta f$. We observe a clear increase of $f_{PO}$ with increasing $\Delta f$ which almost follows the expected linear dependence according to $f_{PO} = \Delta f$ as indicated by the dashed line. Furthermore, we simulate the dependence of the oscillation frequency on the mode splitting up to 80 GHz and find the same correspondence, as depicted in Figure 4b. Deviations from this direct correspondence can be explained with the dependence of the $f_{PO}$ on further laser properties such as photon density, photon lifetime, carrier recombination rate, spin-flip rate, linewidth enhancement factor and saturation effects, especially in the low birefringence regime used here.[6]

Overall, the $f_{PO}(\Delta f)$ dependence highlights that the polarization-oscillation frequency can be predetermined by the fundamental mode splitting of micropillars which we engineer by the ellipticity of the pillar cross-section. As long as the dynamics of the coupled carrier-spin photon-spin system are sufficiently fast, the oscillations are expected to follow the mode splitting even to much higher frequencies. The simulations are based on the same set of parameters, except for the birefringence rate, that was used to describe the transient polarization dynamics in Figure 3. The frequency range between 14 and 20 GHz, marked in red, reflects a region with different, more complex polarization dynamics including chaos. Here the simulated transients do not show damped polarization oscillations. Different dynamic regions in spin-VCSELs are known to depend strongly on device parameters such as spin-flip rate, birefringence and dichroism.[21] For our set of parameters, the complex dynamics are suppressed for high birefringence rates where single period polarization oscillations can be observed again.

It is interesting to note that while conventional fast laser concepts are limited by the resonance frequency of the electron–photon-dynamics, which are practically determining the intensity modulation frequency, the modulation speed of spin-lasers benefits from short spin-lifetimes and the extremely high resonance frequency of the carrier-spin-polarization system. This frequency is mainly determined by the mode splitting and is completely independent from the carrier-photon dynamics or intensity dynamics limitations, respectively. Together with the high values for the birefringence, this indicates the potential of this novel type of high-$\beta$ spin-laser. Indeed, first preliminary results based on numerical simulations using the spin-flip model indicate that modulation frequencies of at least 200 GHz should be possible even for higher effective gain dichroism, e.g., due to different $Q$ factors. Deviations from the direct correspondence between the polarization-oscillation frequency $f_{PO}$ and the mode splitting $\Delta f$ as depicted in Figure 4a can be fundamentally explained with the dependence of $f_{PO}$ on further laser properties such as photon density, photon lifetime, carrier recombination rate, spin-flip rate, linewidth enhancement factor and saturation effects, especially in the low birefringence regime used here.[5] For one of the two samples with nominal 16% ellipticity the obtained dynamics remain $\approx 2$–3 GHz below the expected value given by the mode splitting. Further experimental and theoretical studies are required to gain a thorough understanding of this variation and whether it is specific to high-$\beta$ CQED lasers.

The relationship between very high $\beta$ factors and a high modulation bandwidth has not yet been fully explored, even with conventional micropillar lasers based on carrier-photon dynamics. While on the one hand one could expect that high $Q$-factors and high $\beta$-factors could lead to fundamentally higher dynamics due to the Purcell effect and associated shorter carrier lifetimes,[22] the larger photon lifetimes of high-$Q$ microcavities would actually be detrimental for the modulation bandwidth. Consequently, a trade-off between higher $\beta$-factors and conventional higher modulation bandwidth can be expected. Interestingly, the situation is very different for our novel spin-micropillar laser concept. For large birefringence, the influence of a large photon lifetime on the polarization resonance frequency is negligible (see Equation (1) in ref. [5]). Consequently, we are not expecting a direct trade-off between large $\beta$-factors and a large polarization modulation bandwidth in spin-micropillar lasers, which is potentially an additional advantage of polarization modulation in spin-micropillar lasers in comparison to intensity modulation in conventional micropillar-lasers.

4. Conclusion

In conclusion, we studied spin-lasing properties in high-$\beta$ microlasers for the first time. Such lasers are highly interesting for the realization of the spin-lasing effect because of their compactness, low-power operation and the strong lateral mode confinement. The latter allowed us to induce a bimodal behavior in pillars with
are achievable in strongly elliptical QD-micropillars,\textsuperscript{23} which
ative small etch rate of
To later realize steep and smooth sidewalls an etching recipe with a rel-
ination of a suitable etchmask material for the ICP-RIE etching process.
μ
1
2
2
2, which was achieved through the deposition of 2.5 monolayers
thick GaAs cavity containing a single layer of InGaAs QDs sand-
thick Al\textsubscript{0.9}Ga\textsubscript{0.1}As/GaAs mirror pairs. The QDs embedded in the middle of the central GaAs cavity were
formed by self-assembled Stranski–Krastanow growth. To secure a high
gain factor the QD growth was optimized for a sheet density of about 1 ×
10\textsuperscript{10} cm\textsuperscript{-2}, which was achieved through the deposition of 2.5 monolayers
of In\textsubscript{0.4}Ga\textsubscript{0.6}As.

5. Experimental Section

Sample Growth: The sample was grown via metalorganic vapor-phase
epitaxy (MOVPE). The layers form a planar microcavity made up by a cen-
tral one-λ thick GaAs cavity containing a single layer of InGaAs QDs sand-
wiched between a lower and an upper distributed Bragg reflector (DBR) composed of 27 (lower) and 23 (upper) λ/4-thick Al\textsubscript{0.9}Ga\textsubscript{0.1}As/GaAs mirror
pairs. The QDs embedded in the middle of the central GaAs cavity were
formed by self-assembled Stranski–Krastanow growth. To secure a high
gain factor the QD growth was optimized for a sheet density of about 1 ×
10\textsuperscript{10} cm\textsuperscript{-2}, which was achieved through the deposition of 2.5 monolayers
of In\textsubscript{0.4}Ga\textsubscript{0.6}As.

Micropillar Fabrication: The micropillar fabrication started with the for-
mation of a suitable etchmask material for the ICP-RIE etching process.
To later realize steep and smooth sidewalls an etching recipe with a rel-
sive small etch rate of ≈100 nm min\textsuperscript{-1} and a composition of Cl\textsubscript{2}, BCl\textsubscript{3}, and Ar\textsubscript{2} was chosen and therefore a dielectric SiN hardmask was needed, which provided the suitable selectivity for the etching process. At the first
step the SiN got deposited at an electrode temperature of 300 °C using plasma enhanced chemical vapor deposition (PECVD) to form a 550 nm
thick hardmask layer. Afterwards the sample was coated with a negative
tone electron beam lithography resist (AZ nlof 2000 series, 0.5 μm grade)
of the same thickness. During the electron beam lithography process the
sample got exposed to the electron beam and the elliptical cross-section of
the micropillars was written into the resist. After development, the re-
sist mask was used to transfer the mask pattern into the hardmask layer
by etching the SiN with a RIE recipe with a hardmask. At the first
etching the sample got cleaned of the remains of the SiN by another
RIE process using CF\textsubscript{4} as the etch gas.

Experimental Setup: The experimental setup is depicted in Figure 5.
For the optical studies the sample was placed in a cryostat with move-
able stage and a focusing lens in front of it. The excitation path was com-
posed of two laser sources for optical pumping. A power adjustable diode
laser which is driven in CW mode was used to operate the laser above
threshold. Additionally, a mode-locked Titanium:Sapphire (Ti:Sa) laser,
which was driven in ps pulsed mode was applied for optical spin injec-
tion. A logarithmic grey filter wheel at the output of the Ti:Sa laser allowed
to tune the power fraction of pulsed optical excitation. The filter wheel
was followed by a linear polarizer and a λ/4-plate which were adjusted
to translate the linear polarization of the Ti:Sa laser to circular polariza-
tion, thus enabling optical spin injection. A beam splitter was used to
combine the two excitation lasers to a common excitation path. A sec-
ond grey filter wheel was added to the combined excitation path to tune
the total optical pumping. This experimental configuration allowed for an
hybrid excitation scheme in which the generation of unpolarized and po-
larized charge carriers can conveniently be adjusted by the included filter
elements.

Using a combination of beam splitters and mirrors three detection
paths were created, each equipped with a λ/4-plate or a λ/2-plate and a
linear polarizer for polarization selective analysis of microlaser emission.
The first detection path diverted a (constant) fraction of the combined
excitation path for power control. The second and third detection paths
concerned the signal of the sample, one of which was terminated with a
monochromator with an attached CCD camera with a spectral resolu-
tion of 33 μeV while the other path was coupled to a streak camera with 4 ps time resolution. Hence, simultaneous time and spectrally resolved
recording was possible in this configuration. An additional 950 nm long
pass filter in front of the streak camera was used to isolate the micropillar
signal from the spectral components of the optical pumping. Finally, a re-
moveable mirror can be added to the detection path to temporarily couple
in a white light source and white light camera for adjusting the sample
inside the cryostat.
Power at \( p = 0.5 \) (see blue curve in Figure 2). The fit reveals a threshold pumping carrier-spin polarization utilizing several laser parameters \([17,26]\). In accordance with those reported \([25]\) for very similar microlasers based on the same wafer material.

### Table 1. Parameters and their values used for simulations with the spin-flip model.

| Symbol | Parameter | Value | Dimension |
|--------|-----------|-------|-----------|
| \( \alpha \) | Linewidth enhancement factor | 2 | |
| \( \beta \) | \( - \) Factor | 0.04 | |
| \( \gamma \) | Carrier decay rate | 5 | ns\(^{-1}\) |
| \( \gamma_{sp} \) | Linear dichroism | 3 | ns\(^{-1}\) |
| \( \tau_{p} \) | Linear birefringence | 6.5e (Figure 3) | GHz |
| \( \gamma_{s} \) | Spin decay rate | 50 | ns\(^{-1}\) |
| \( \kappa \) | Photon decay rate | 50 | ns\(^{-1}\) |
| \( J \) | Unpolarized bias pumping | 7 | (times threshold) |
| \( \eta_{0} \) | Norm. pumping pulse amplitude | 12 | |
| \( \eta \) | Pumping polarization | \(-0.3\) | |
| \( \tau \) | Pumping pulse duration | \( 2.5 \times 10^{-3} \) | ns |

Rate-Equation Modelling of the Input–Output Dependence of the Micro-laser: A rate-equation approach was used for fitting the experimental data depicted in Figure 2, and for extracting the mutually dependent microlaser parameters \( \beta \) and \( \gamma \). The model assumes negligible nonradiative recombinations and relates the excitation intensity \( I \) to the intracavity photon number \( p \) as follows \([24]\):

\[
I(p) = A \times \left[ \frac{p}{1 + p} \times (1 + \zeta) \times (1 + \beta p) - \zeta \beta p \right]
\]

(1)

which includes the transparency parameters \( \zeta = \frac{n_0}{\tau_{ph}} \), and \( \gamma = \frac{n_{sp}}{\tau_{sp}} \) with \( n_0 \) being the transparency carrier density, \( \beta \) the spontaneous emission coupling factor, \( \gamma \) the cavity decay rate, \( \tau_{sp} \) and \( \tau_{ph} \) the spontaneous emission and photon lifetime, respectively, \( \nu_{L} \) the frequency of the lasing mode, \( Q \) the cavity quality factor, and \( \delta \) the photon conversion efficiency \([24,25]\). The fit function is found by solving the equation above for \( p(I) \). A good fit of the experimental data can be achieved by \( \zeta = 3 \), \( \beta = 4\% \) and \( \gamma = 0.5 \) (see blue curve in Figure 2). The fit reveals a threshold pumping power at \( p = 1 \) of \( I_{th} = 2.1 \) mW. Noteworthy, these values are in good agreement with those reported \([25]\) for very similar microlasers based on the same wafer material.

Spin-Flip Model: The spin-flip model is a set of coupled rate equations, which relate the electrical fields, the differential carrier density, and the carrier-spin polarization utilizing several laser parameters \([17,26]\). In accordance to the notation used \([24]\) the pumping term was used

\[
\eta_{sp} = \eta_{0} \pm \beta \frac{p}{1 + p} \exp \left( - \frac{2J^2}{\nu_{s}} \right) + \frac{J}{2}
\]

(2)

The list of parameters and their values can be found in Table 1. Gain compression was neglected and spontaneous emission noise was included using complex Gaussian white noise sources. The calculations for the high-\( \beta \) spin-microlaser are based on a linear gain model. Further details about the influence of nonlinear optical gain can be found \([27]\).

### Conflict of Interest

The authors declare no conflict of interest.

### Data Availability Statement

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

### Keywords

bimodal micropillar cavities, cavity quantum electrodynamics, microlasers, quantum dots, spin-lasers

---

[1] N. Jones, Nature 2018, 561, 163.
[2] N. Haghighi, G. Larisch, R. Rosales, M. Zorn, J. A. Lott, IEEE International Seminar on Semiconductor Laser Conference (ISLSC), 2018, pp. 1–2.
[3] A. Liu, P. Wolf, J. A. Lott, D. Birnberg, Photon. Res. 2019, 7, 121.
[4] N. Yokota, K. Nisaka, H. Yasaka, K. Ikeda, Appl. Phys. Lett. 2018, 113, 171102.
[5] M. Lindemann, G. Xu, T. Pusch, R. Michalzik, M. R. Hofmann, I. Zutić, N. C. Gerhardt, Nature 2019, 568, 212.
[6] I. Zutić, G. Xu, M. Lindemann, P. E. F. Junior, J. Lee, V. Labinc, K. Stojšić, G. M. Sipahi, M. R. Hofmann, N. C. Gerhardt, Solid State Commun. 2020, 316–317, 1.
[7] K. Panajotov, B. Nagler, G. Verschaffelt, A. Georgievski, H. Thienpont, J. Danckaert, I. Veretennicoff, Appl. Phys. Lett. 2000, 77, 1590.
[8] T. Pusch, M. Lindemann, N. C. Gerhardt, M. R. Hofmann, R. Michalzik, Electron. Lett. 2015, 51, 1600.
[9] M. Lindemann, T. Pusch, R. Michalzik, N. C. Gerhardt, M. R. Hofmann, Appl. Phys. Lett. 2016, 108, 042404.
[10] S. Strauf, K. Hennessy, M. T. Rakher, Y.-S. Choi, A. Badolato, L. C. Andreani, E. L. Hu, P. M. Petroff, D. Bouwmeester, Phys. Rev. Lett. 2006, 96, 127404.
[11] G. Björk, A. Karlsson, Y. Yamamoto, Phys. Rev. A 1994, 50, 1675.
[12] W. W. Chow, S. Reitzenstein, Appl. Phys. Rev. 2018, 5, 041302.
[13] C. Gies, S. Reitzenstein, Semicond. Sci. Technol. 2019, 34, 073001.
[14] C. Redlich, B. Lingnau, S. Holzinger, E. Schlottmann, S. Kreinberg, C. Schneider, M. Kamp, S. Höfling, J. Wolters, S. Reitzenstein, K. Lüdge, New J. Phys. 2016, 18, 063011.
[15] E. Schlottmann, D. Schicke, F. Krüger, B. Lingnau, C. Schneider, S. Höfling, K. Lüdge, X. Porte, S. Reitzenstein, Opt Express 2019, 27, 28816.
[16] S. Kreinberg, X. Porte, D. Schicke, B. Lingnau, C. Schneider, S. Höfling, I. Kanter, K. Lüdge, S. Reitzenstein, Nat. Commun. 2019, 10, 1359.
[17] M. San Miguel, Q. Feng, J. V. Moloney, Phys. Rev. A 1995, 52, 1728.
[18] T. Heuser, J. Große, S. Holzinger, M. M. Sommer, S. Reitzenstein, IEEE J. Sel. Top. Quantum Electron. 2020, 26, 1.
[19] M. P. van Exter, R. F. M. Hendriks, J. P. Woerdman, Phys. Rev. A 1998, 57, 2080.
[20] H. A. M. Leymann, C. Hopfmann, F. Albert, A. Foerster, M. Khanbekyan, C. Schneider, S. Höfling, A. Forchel, M. Kamp, J. Wiersig, S. Reitzenstein, Phys. Rev. A 2013, 87, 053819.
[21] Y. Huang, P. Zhou, M. S. Torre, N. Li, I. D. Henning, M. J. Adams, IEEE J. Quantum Electron. 2021, 57, 240012.
[22] H. Altug, D. Englund, J. Vucković, Nat. Phys. 2006, 2, 484.
[23] D. M. Whittaker, P. S. S. Guimaraes, D. Sanvitto, H. Vinck, S. Lam, A. Daraei, J. A. Timpson, A. M. Fox, M. S. Skolnick, Appl. Phys. Lett. 2007, 90, 161105.

[24] S. Reitzenstein, C. Böckler, A. Bazhenov, A. Gorbunov, A. Löffler, M. Kamp, V. Kulakovskii, A. Forchel, Opt. Express 2008, 16, 4848.

[25] L. Andreoli, X. Porte, T. Heuser, J. Große, B. Moeglen-Paget, L. Furfaro, S. Reitzenstein, D. Brunner, Opt. Express 2021, 29, 9084.

[26] A. Gahl, S. Balle, M. San Miguel, IEEEJ. Quantum Electron. 1999, 35, 342.

[27] G. Xu, K. Patel, I. Žutić, Appl. Phys. Lett. 2021, 119, 171104.