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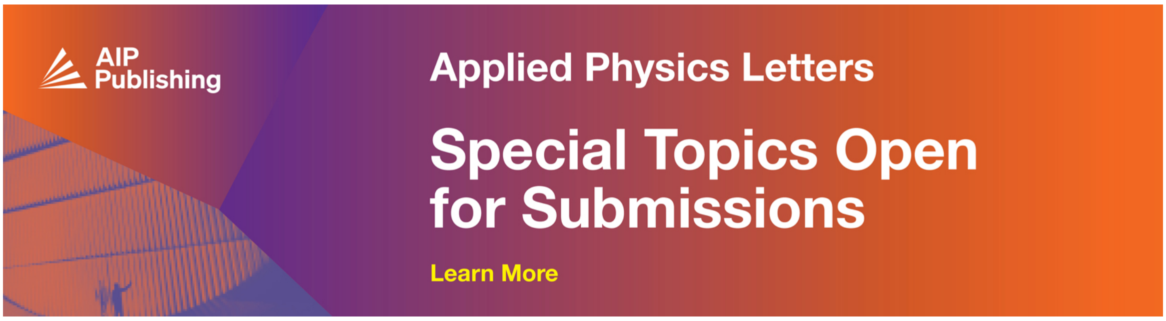

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ABSTRACT

We present a GaSb-based vertical-external-cavity surface-emitting laser (VECSEL) tailored as a low-noise pump source for quantum frequency conversion. The 2062.4 nm emitting VECSEL emits a single-frequency output power of 2.5 W in a linear cavity with an intracavity birefringent filter. With no additional means of wavelength stabilization, the emission wavelength drift over 15 hours was less than 7 pm after the initial thermalization period. After locking the VECSEL to a frequency comb, the beating frequency between the laser and the comb light was characterized. The measurement confirmed a linewidth of less than 350 kHz (FWHM), and the absolute wavelength deviation over 22 hours had a standard deviation of 103.6 kHz. Relative intensity noise (RIN) measurements showed an integrated RIN of 0.15% root mean squared (RMS).

Vertical-external-cavity surface-emitting lasers (VECSELs)[1–3] combine high output power with a circular beam profile and the flexible, engineerable output wavelength of semiconductor gain materials. The highest output powers have been reported for GaAs-based VECSELs emitting around 1 μm, reaching more than 100 W for multimode operation[4] and more than 20 W for single-frequency operation.[5] VECSELs based on the GaSb material system emitting around 2 μm have also been shown to reach up to 17 W in multimode operation,[6] but the highest reported single frequency output power has been 1 W.[7]

Recently there has been a growing demand for single frequency sources in the 2 μm wavelength range, e.g., for gravitational wave detectors[8] and for quantum applications such as Rydberg-atom-based radio frequency sensing[9] or quantum frequency conversion (QFC). Quantum frequency conversion (QFC) is a key enabling technology for large-scale, fiber-linked quantum networks. It enables the transduction of photons emitted by quantum memories—typically in the visible to near-infrared spectrum—into the low-loss telecom band around 1550 nm.[10] This process can be achieved through parametric downconversion via difference frequency generation in a periodically poled lithium niobate (PPLN) waveguide, where single photons carrying quantum information are mixed with a strong coherent laser beam in the infrared, resulting in downconversion.

However, direct single-step conversion to 1550 nm from visible wavelengths often requires a mixing laser with higher energy than the target wavelength. This introduces significant conversion-induced noise, primarily due to spontaneous parametric downconversion of the high-energy pump laser.[11,12]

To mitigate this issue, recent developments in two-stage QFC devices[13,14] have demonstrated noise reduction by using a mixing laser with only half the energy, i.e., double the wavelength. This approach involves first converting the input photons to an intermediate wavelength, followed by a second conversion to the target telecom wavelength. For example, single photons emitted by tin-vacancy centers in diamond at 619 nm can be down-converted to 1550 nm using a mixing laser at 2062 nm in a two-step conversion scheme.[15]

Achieving optimal conversion efficiency in such systems requires high pump powers, typically exceeding 1 W. Furthermore, the spectral properties of the photons must be preserved during conversion: the pump laser must provide a long-term stable output wavelength in order to keep the converted photons indistinguishable as well as maintain a sub-MHz linewidth (it needs to be more than one order of magnitude narrower than the linewidth of the SnV sources in the range of 20 MHz[16,17]). In this paper, we will present a VECSEL fulfilling all these requirements.

The semiconductor heterostructure used consists of 10 ternary, compressively strained, 10 nm thick InGaSb quantum wells (QWs) placed in a resonant-periodic gain arrangement in a $6\lambda/2$ subcavity made from lattice-matched $Al_{0.30}Ga_{0.70}As_{0.02}Sb_{0.98}$ barriers grown on top of a DBR made of 22.5 pairs of GaSb and lattice-matched AsAsSb. The structure is designed for a pump wavelength of 980 nm with a theoretical pump absorption of more than 92% in a single pass of the active region. No pump resonance or pump DBR was used, i.e., the transmitted light not absorbed in the barriers will be absorbed in the DBR and dissipated as heat. The number of QWs in the individual antinodes of the optical field is determined by the absorbed pump power in the associated barrier volume, resulting in a (1-)3-2-2-1-1(-0) QW arrangement with one QW in the half antinode directly behind the cap and window (10 nm barrier layer between window and the QW), 3 QWs with a 20 nm barrier between QWs in the first full antinode near the cap, and only 1 QW in the last full antinode near the DBR. The structure was grown on 2″ GaSb substrates in an "Epi 1040" MBE from Veeco with a growth temperature of 530 °C for the DBR and around 415 °C for the active region. The wafer was thinned to 80 µm and cleaved to individual chips with an edge length of $3 \times 3\,mm^2$, then liquid capillary bonded to uncoated $4 \times 4\,mm^2$ SiC intracavity heatspreaders with a thickness of 500 µm.

The used VECSEL chip was first characterized in multimode operation with a linear resonator with a length of 30 mm and a concave outcoupling mirror with −50 mm radius of curvature (ROC) and 96% reflectivity. The mode spot diameter on the chip was calculated by the ABCD matrix method to be 255 µm. In this standard setup at 20 °C heatsink temperature and with a pump spot diameter of 720 µm, the VECSEL chip yielded a maximum output power of 4.8 W and a slope efficiency (relative to transmitted pump power, i.e., with correction of the reflectivity of the front SiC surface) of 18.5% (Fig. 1). This output power level is comparable to the values cited in other publications using 980 nm pumping and a SiC intracavity heatspreader.[18,19] At a heatsink temperature $T_{HS} = 20\,°C$, the central emission wavelength shifted from 2040 nm near the laser threshold to 2085 nm at the thermal rollover of the laser.

For single frequency operation, the chip was placed in a 51 mm long linear resonator with a birefringent filter (3 mm thick quartz) for coarse wavelength tuning and a ROC = −150 mm, concave outcoupling mirror with 96% reflectivity mounted on a piezo-actuator for control of the cavity length. This resonator design results in a calculated mode spot diameter of 430 µm on the chip without consideration of the thermal lens forming in the SiC heatspreader and chip as an effect of the internal heating.[20] Increasing the thermal lens has little to no effect down to a focal length around 40 mm, where the mode spot diameter becomes larger than 440 mm. This range of permissible focal lengths of the thermal lens makes the resonator virtually invariant for all practically relevant operating conditions.[20] To achieve single lateral mode operation, the pump spot diameter was adjusted to the mode spot diameter within the limits of measurement accuracy.

The emission wavelength was coarsely tuned using the birefringent filter placed in the linear cavity at Brewster's angle. As the SiC intracavity heatspreader acts as a Fabry–Pérot etalon, this coarse tuning results in mode hops with a mode spacing of 1.6 nm. Fine tuning of the emission wavelength can be achieved by varying the temperature of the SiC etalon (i.e., the chip temperature) and the cavity length via the piezoelectric transducer. The target wavelength could be achieved with a heatsink temperature of 7 °C, resulting in the spectrum shown in Fig. 2(a). As this temperature would lead to condensation of ambient air humidity, the laser-module had to be purged by nitrogen or dry air. With this setup, the VECSEL emitted 2.5 W of output power in single frequency operation, which was confirmed by the Fabry–Pérot interferometer (FPI) trace [Fig. 2(b)].

The stability of the output power and emission wavelength in this free running state (without active wavelength stabilization, only temperature stabilization of the submount, resonator, and pump laser, as well as closed housing of the resonator with nitrogen purging) is shown in Fig. 3, where the emission wavelength measured with a wavemeter with 0.4 pm resolution is plotted vs time. After the initial thermalization period (≈1.1 h), a stable operation without mode hops (cavity mode spacing 40 pm) and a very low drift of the emission wavelength of less than 7 pm over 14 hours of operation is reached. The standard deviation over this time period was 1.17 pm, which is equivalent to 82.5 MHz.

To meet the strict requirements of quantum frequency conversion, the wavelength has to be stabilized to a reference. For this we used a frequency comb from MENLO Systems with spectral lines up to 2150 nm and 100 MHz spacing of the comb modes. The comb is referenced to an internal 10 MHz Oven Controlled Crystal Oscillator (OXCO) with an absolute stability of $1.0 \times 10^{-9}\,s^{-1}$ and a short-term stability of $1.0 \times 10^{-10}\,s^{-1}$.

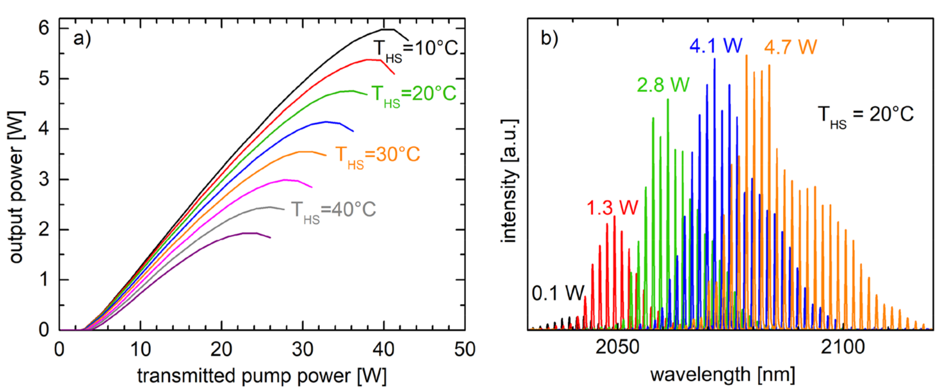

FIG. 1. Basic characterization of the used VECSEL chip in multimode operation. (a) Output power vs transmitted pump power (80% of incident pump power, accounting for 20% reflection on the front SiC surface) for different heatsink temperatures T_{HS}. (b) Emission spectra at $T_{HS} = 20\,°C$ for different output powers.

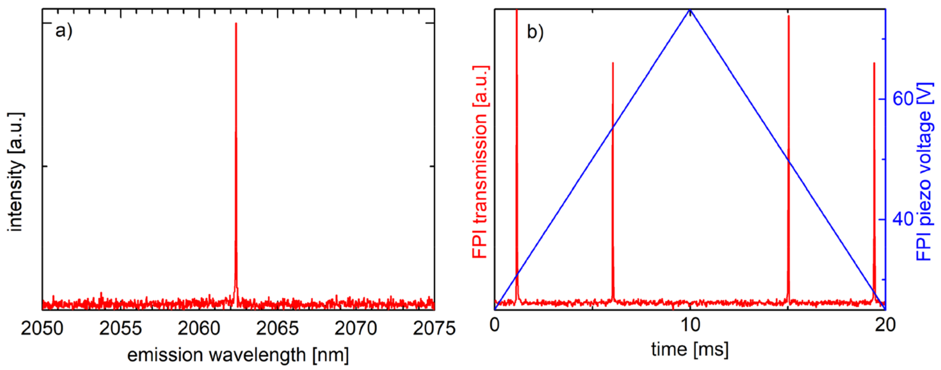

FIG. 2. (a) Emission spectrum after tuning the wavelength to the target wavelength of 2062.4 nm and (b) FPI transmission and piezo voltage of a 1 GHz-FPI vs time, showing single frequency emission.

In order to establish the feedback loop, we use the residual light reflected from the intracavity birefringent filter. A small fraction of this light was fiber-coupled (2 mW in a single-mode PM fiber) and superimposed with the filtered comb light (1 nm bandpass filter at 2062 nm) in the beat detection unit, resulting in a clearly resolved beat note with a 45 dB SNR (100 kHz RBW). This CW beat was then compared to an RF reference at 40 MHz and the resulting error signal is fed into a fast PID controller, which controls the piezo-actuator changing the cavity length of the VECSEL resonator. A phase lock with 1 kHz bandwidth was achieved, locking the beat frequency to the setpoint at 40 MHz.

Figure 4 shows the frequency spectrum of the beat note between the VECSEL light and the light of one of the comb modes measured with an integration time of 3.6 s, showing a full width at half maximum (FWHM) value of 360 kHz. This value is equivalent to an upper limit of the spectral linewidth of the VECSEL, as the beat frequency distribution is dominated by the linewidth of the VECSEL (the linewidth of the comb is in the range of 10 kHz). It should be noted that the free running linewidth of the VECSEL is close to this value, as this setup is designed to stabilize the center wavelength with a bandwidth of 1 kHz but can only marginally reduce the linewidth of the laser for higher frequencies. In order to establish an effective linewidth reduction, a faster actuator would be needed.

Despite the high output power of the reported VECSEL, this measured spectral linewidth is comparable to other reported linewidth measurements of single-frequency, GaSb-based VECSELs without active stabilization: For output powers up to 960 mW, Kaspar *et al.*[20] reported a linewidth of 220 kHz (45 kHz) measured with a heterodyne beat-note technique with a much shorter sampling time of 0.1 s (100 μs), Reed and Bedford[21] reported 500 kHz at 120 mW. For much smaller output powers around 5 mW, there have been reports of GaSb VECSELs with linewidths <20 kHz.[22] A high-power, InGaAs-based, single-frequency VECSEL emitting at 1013 nm was reported to have a linewidth of 1.78 MHz for a sampling time of 1 s (407 kHz for 1 ms).[5] For lower wavelengths around 670 nm and output powers around 40 mW, there have been reports of very low linewidths in the kilohertz range[23] or even below[24] by using a monolithic cavity made from fused silica, which eliminates or reduces many environmental influences.

Figure 5 shows the deviation of the beat frequency between one comb mode and the temperature stabilized, nitrogen-purged, and frequency locked VECSEL from the setpoint of 40 MHz over a time period of 22 hours. The measurement documents a stable, locked operation over the whole measurement time without mode hops. The standard deviation of the beat frequency in this time frame was 103.6 kHz, which is equivalent to 1.46 fm wavelength deviation, and much lower

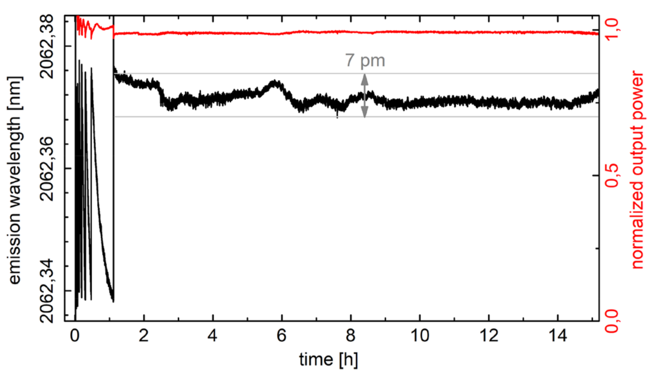

FIG. 3. Emission wavelength (black) and output power (red) of the VECSEL measured over 15 hours with a wavemeter. No active wavelength locking was used for this measurement, just thermal stabilization of the laser setup (submount, resonator, and pump laser) and housing the resonator in a closed module purged with nitrogen. Part of the visible short time fluctuations correspond to the resolution limit of the wavemeter of 0.4 pm.

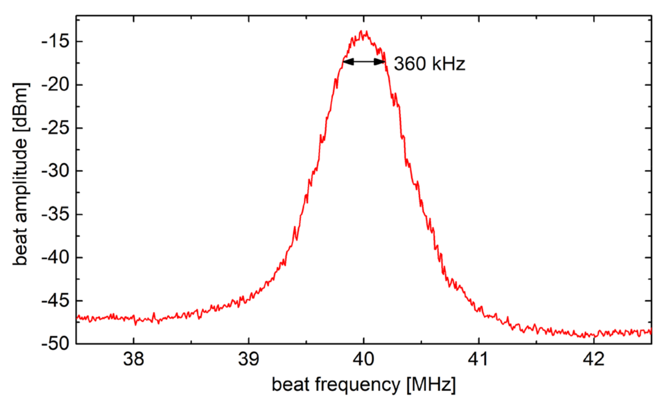

FIG. 4. Frequency spectrum of the beat note between the frequency locked VECSEL and one of the spectral lines of the comb measured with an integration time of 3.6 s. The FWHM (measured at −3 dB of the maximum) of the distribution is 360 kHz.

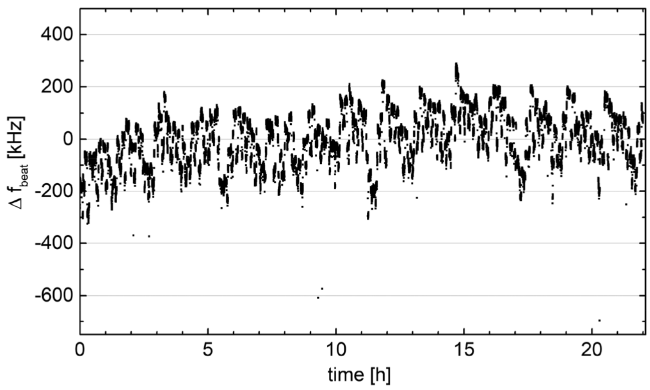

FIG. 5. Deviation of the beat frequency Δf_{beat} between the comb and the thermally stabilized, nitrogen-purged, and frequency locked VECSEL from the set value over a time period of 22 hours. The standard deviation of the values is 103.6 kHz.

than the limit of 1 MHz necessary for quantum frequency conversion (see Introduction).

The relative intensity noise (RIN) of the VECSEL at 2.5 W was measured by analyzing the signal of a photodiode with a bandwidth of 20 MHz. The resulting RIN spectrum is shown in Fig. 6. The RIN values in both cases are above −100 dBc/Hz up until frequencies around 200 Hz, dropping to a noise floor of around −110 dBc/Hz up until frequencies of 100 kHz. The narrow peaks visible around and above 1 MHz are caused by interference in the measurement setup and not caused by the laser itself. The second set of curves shows the integrated RIN plotted against the upper integration limit (the lower integration limit of the used equipment is 9 Hz), resulting in a very similar total value of 0.14% RMS (root mean squared) and 0.15% RMS for the locked and free running VECSEL, respectively. The differences between locked and free running VECSEL are, as expected, small with only minor differences.

In the GaAs material system and for a lower output power of 800 mW, Laurain *et al.*[25] reported comparable or higher RIN values in the frequency range below ≈300 Hz and lower RIN levels for the

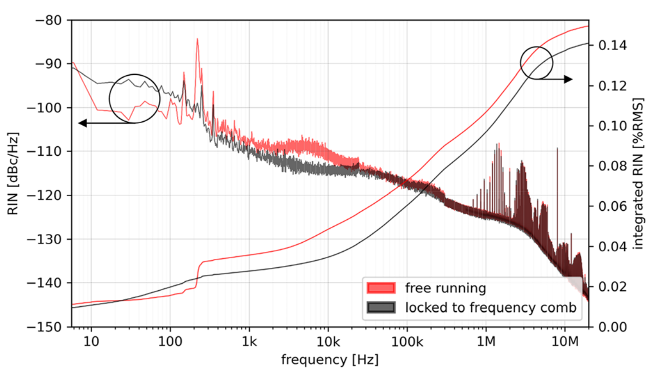

FIG. 6. Relative intensity noise (RIN) of the single frequency VECSEL at an output power of 2.5 W in free running operation (red) and locked to the frequency comb (black). The narrow peaks around and above 1 MHz are caused by interference in the measurement setup and are not caused by the laser itself. The right axis shows the integrated RIN plotted against the upper integration limit (the low frequency limit of the used equipment is 9 Hz).

remaining frequency range. The difference can be attributed to higher pump induced noise in our case from the used multimode, multi-chip, fiber-coupled 980 nm pump module, as the pump RIN is directly influencing the VECSEL RIN.[26] Using a monolithic cavity made from fused silica, Lee *et al.*[23] also showed higher RIN levels for low frequencies up to ≈10 kHz and lower RIN levels above that for a free running pump source. Lee *et al.* reported that the VECSEL RIN dropped 30 dB in the frequency range below 1 kHz when using active pump power stabilization, highlighting the influence of the pump induced noise. The influence of the pump noise is also visible in Ref. 27, where high pump noise results in VECSEL RIN levels significantly higher than those presented here.

In conclusion, we presented a GaSb-based VECSEL with a single-frequency output power of 2.5 W and an emission wavelength of 2062.4 nm. The unlocked laser showed an emission wavelength drift lower than 7 pm over 15 hours after the initial thermalization. When locked to a frequency comb, the long-term deviation from the setpoint of the beat frequency between the comb and the laser emission had a standard deviation of 103.6 kHz, and the linewidth was measured to be 360 kHz (FWHM). The integrated RIN was measured to be 0.15% RMS in the measurement bandwidth between 9 Hz and 20 MHz.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Peter Holl: Conceptualization (equal); Data curation (equal); Investigation (equal); Visualization (equal); Writing – original draft (lead); Writing – review & editing (equal). **Steffen Adler:** Conceptualization (equal); Data curation (equal); Investigation (equal); Visualization (equal); Writing – review & editing (equal). **Elke Diwo-Emmer:** Conceptualization (supporting); Data curation (supporting); Investigation (equal); Resources (equal); Writing – review & editing (equal). **Andreas Bächle:** Conceptualization (supporting); Data curation (supporting); Investigation (equal); Resources (equal); Writing – review & editing (equal). **Maximilian Bradler:** Conceptualization (equal); Data curation (equal); Investigation (equal); Resources (equal); Writing – review & editing (equal). **Milad Yahyapour:** Conceptualization (equal); Data curation (equal); Investigation (equal); Writing – review & editing (equal). **Ronald Holzwarth:** Conceptualization (equal); Data curation (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal). **Marlon Schäfer:** Conceptualization (supporting); Data curation (equal); Investigation (equal); Validation (equal); Writing – review & editing (equal). **Christoph Becher:** Conceptualization (supporting); Data curation (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal). **Marcel Rattunde:** Conceptualization (equal); Data curation (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

REFERENCES

[1]M. Kuznetsov, F. Hakimi, R. Sprague, and A. Mooradian, "High-power (0.5 W CW) diode-pumped vertical-external-cavity surface-emitting semiconductor lasers with circular TEM beams," IEEE Photonics Technol. Lett. **9**(8), 1063 (1997).

[2]M. Guina, A. Rantamäki, and A. Härkönen, "Optically pumped VECSELs: Review of technology and progress," J. Phys. D:Appl. Phys. **50**(38), 383001 (2017).

[3]A. C. Tropper, H. D. Foreman, A. Garnache, K. G. Wilcox, and S. H. Hoogland, "Vertical-external-cavity semiconductor lasers," J. Phys. D:Appl. Phys. **37**(9), R75 (2004).

[4]B. Heinen, T.-L. Wang, M. Sparenberg, A. Weber, B. Kunert, J. Hader, S. Koch, J. Moloney, M. Koch, and W. Stolz, "106 W continuous-wave output power from vertical-external-cavity surface-emitting laser," Electron. Lett. **48**(9), 516 (2012).

[5]F. Zhang, B. Heinen, M. Wichmann, C. Möller, B. Kunert, A. Rahimi-Iman, W. Stolz, and M. Koch, "A 23-watt single-frequency vertical-external cavity surface-emitting laser," Opt. Express **22**(11), 12817–12822 (2014).

[6]P. Holl, M. Rattunde, S. Adler, A. Bächle, E. Diwo-Emmer, R. Aidam, and J. Wagner, "GaSb-based 2.0 μm SDL with 17 W output power at 20 °C," Electron. Lett. **52**(21), 1794–1795 (2016).

[7]S. Kaspar, M. Rattunde, T. Töpper, C. Manz, K. Köhler, and J. Wagner, "Semiconductor disk laser at 2.05 μm wavelength with <100 kHz linewidth at 1 W output power," Appl. Phys. Lett. **100**(3), 031109 (2012).

[8]P. Baer, P. Cebeci, M. Reiter, F. Bontke, M. Giesberts, and H.-D. Hoffmann, "Ultra-low-noise, single-frequency, all-PM thulium- and holmium-doped fiber amplifiers at 1950 and 2090 nm for third-generation gravitational wave detectors," IEEE Photonics J. **16**(1), 1 (2024).

[9]S. M. Bohaichuk, F. Ripka, V. Venu, F. Christaller, C. Liu, M. Schmidt, H. Kübler, and J. P. Shaffer, "Three-photon Rydberg-atom-based radio-frequency sensing scheme with narrow linewidth," Phys. Rev. Appl. **20**(20), L061004 (2023).

[10]S. Wehner, D. Elkouss, and R. Hanson, "Quantum internet: A vision for the road ahead," Science **362**(6412), eaam9288 (2018).

[11]A. Dréau, A. Tchebotareva, A. E. Mahdaoui, C. Bonato, and R. Hanson, "Quantum frequency conversion of single photons from a nitrogen-vacancy center in diamond to telecommunication wavelengths," Phys. Rev. Appl. **9**(6), 064031 (2018).

[12]S. Zaske, A. Lenhard, and C. Becher, "Efficient frequency downconversion at the single photon level from the red spectral range to the telecommunications C-band," Opt. Express **19**(13), 12825–12836 (2011).

[13]M. Schäfer, B. Kambs, D. Herrmann, T. Bauer, and C. Becher, "Two-stage, low noise quantum frequency conversion of single photons from silicon-vacancy centers in diamond to the telecom C-band," Adv. Quantum Tech. **8**(2), 2300228 (2025).

[14]F. von Chamier, J. Hanel, C. Müller, W. Li, R. A. Kögler, and O. Benson, "Low-noise cascaded frequency conversion of 637.2 nm light to the telecommunication C-band in a single-waveguide device," Opt. Express **33**(10), 21650–21659 (2025).

[15]D. Lindler, T. Bauer, M. Schäfer, and C. Becher, "Two-stage quantum frequency conversion for SnV-resonant photons to the telecom C-band," in *Optica Quantum 2.0 Conference and Exhibition* (Optica Publishing Group, 2023), p. QW4A.1.

[16]J. Görlitz, D. Herrmann, P. Fuchs, T. Iwasaki, T. Taniguchi, D. Rogalla, D. Hardeman, P.-O. Colard, M. Markham, M. Hatano und, and C. Becher, "Coherence of a charge stabilised tin-vacancy spin in diamond," npj Quantum Inf. **8**, 45 (2022).

[17]J. Görlitz, D. Herrmann, G. Thiering, P. Fuchs, M. Gandil, T. Iwasaki, T. Taniguchi, M. Kieschnick, J. Meijer und, and M. Hatano, "Spectroscopic investigations of negatively charged tin-vacancy centres in diamond," New J. Phys. **22**, 013048 (2020).

[18]M. Gaulke, M. C. Schuchter, N. Huwyler, M. Golling, B. Willenberg, C. R. Phillips, and U. Keller, "Optically pumped GaSb-based thin-disk laser design considerations for CW and dual-comb operation at a center wavelength around 2 μm," IEEE J. Sel. Top. Quantum Electron. **31**(2), 1 (2025).

[19]M. Rattunde, P. Holl, and J. Wagner, "Single-frequency and high power operation of 2–3 micron VECSEL," in *Vertical External Surface Emitting Lasers* (Wiley-VCH, Berlin, 2021), pp. 63–107.

[20]S. Kaspar, M. Rattunde, T. Töpper, B. Rösener, C. Manz, K. Köhler, and J. Wagner, "Linewidth narrowing and power scaling of single-frequency 2.X μm GaSb-based semiconductor disk lasers," IEEE J. Quantum Electron. **49**(3), 314–324 (2013).

[21]J. M. Reed and R. G. Bedford, "Tunable, single-longitudinal mode 2 μm VECSEL," in *Frontiers in Optics + Laser Science* (Optica Publishing Group, 2019), p. JTu3A.57.

[22]A. Garnache, A. Ouvrard, and D. Romanini, "Single-frequency operation of external-cavity VCSELs: Non-linear multimode temporal dynamics and quantum limit," Opt. Express **15**(15), 9403–9417 (2007).

[23]M. Lee, P. H. Moriya, and J. E. Hastie, "Monolithic VECSEL for stable kHz linewidth," Opt. Express **31**(23), 38786–38797 (2023).

[24]P. H. Moriya, M. Lee, and J. E. Hastie, "Sub-kilohertz linewidth free-running monolithic cavity VECSEL with 10 − 12 stability," Appl. Phys. Lett. **125**(2), 021101 (2024).

[25]A. Laurain, M. Myara, G. Beaudoin, I. Sagnes, and A. Garnache, "Multiwatt-power highly-coherent single-frequency tunable vertical-external-cavity-surface-emitting-semiconductor-laser," Opt. Express **18**(14), 14627–14636 (2010).

[26]M. Myara, M. Sellahi, A. Laurain, A. Michon, I. Sagnes, and A. Garnache, "Noise properties of NIR and MIR VECSELS," in *Proceedings of the SPIE, Volume 8606: Vertical External Cavity Surface Emitting Lasers (VECSELs) III* (SPIE, 2013), p. 86060Q.

[27]P. H. Moriya, R. Casula, G. A. Chappell, D. C. Parrotta, S. Ranta, H. Kahle, M. Guina, and J. E. Hastie, "InGaN-diode-pumped AlGaInP VECSEL with sub-kHz linewidth at 689 nm," Opt. Express **29**(3), 3258–3268 (2021).